Environmentally-Benign Imidazolium-Based Ionic Liquids: Synthesis, Characterisation and Applications in Hydrogenation Reactions

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For the award of PhD in Organic Chemistry

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Dedicated to Nana and Grandad

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of PhD in organic chemistry is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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Synthesis, Characterisation and Applications in Hydrogenation Reactions
Saibh Morrissey

A library of novel achiral imidazolium ionic liquids (ILs) comprising an ester functionality were synthesised and characterised. From the library, the synthesis and characterisation of 94 novel compounds are covered in this thesis. In order to compare the affect of the ester functionality on the biodegradation of the ILs, amide derivatives were prepared. The toxicity of the ILs was investigated (*), with most ILs being non-toxic to bacteria. The biodegradability of the [$OctOSO_3$] ILs was measured (**). Biodegradability of 55 – 66 % was obtained for the ester containing [$OctOSO_3$] ILs, while biodegradabilities ranging from 29-36 % was obtained with the amide derivatives. Chirality was introduced to the novel ILs with the incorporation of mandelate and lactate moieties in the cations of the ILs. The preparation of 40 mandelate-based ILs and 21 lactate-based derivatives is covered herein. Most [$OctOSO_3$] ILs are shown to be 'readily biodegradable', the mandelate-based [$OctOSO_3$] salts displaying higher biodegradability (65-82 %) than the lactate counterparts (55-74 %).

Heterogeneous hydrogenation reactions were carried out in a selection of the novel achiral ILs. The ILs were shown to be robust to these reactions conditions, with no degradation of the novel reaction media being evident following numerous recycling procedures. Superior results in terms of selectivity were obtained using the novel ILs in comparison to commercially available ILs and common organic solvents.

Heterogeneous and homogeneous hydrogenation of prochiral substrates were carried out in a selection of novel chiral ILs (CIL). Although no enantiomeric excess was seen to be induced from the use of the CILs, their use as robust reaction solvents was demonstrated. These solvents were also shown to have potential as recyclable media. Their potential as chiral additives was also shown, with increased percentage conversion being evident with the addition of small quantities of CIL to an achiral IL as reaction solvent.

* Toxicity studies were carried out by Dr. Bríd Quilties group in DCU

** Biodegradability studies were carried out at the 'Department of Surfactant Technology, IIQAB-CSIC, Jordi Girona 18-26, 08034, Spain' by M. Teresa Garcia

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Publications List

- **Biodegradable solvents for the chemical industry** *N. Gathergood, B. Pegot, S. Morrissey,* Irish patent (2007/0597) filed 21st August 2007, PCT patent (PCT/EP2008/060978) pending
- **Oxygen-functionalized ionic liquids: the key to reduced toxicity and increased biodegradability** *S. Morrissey, B. Pegot, D. Coleman, M.T. Garcia, B. Quilty, N. Gathergood* submitted for publication to Green Chemistry (RSC Publishing)
- **Selective hydrogenation of *trans*-cinnamaldehyde and hydrogenolysis-free hydrogenation of benzyl cinnamate in imidazolium ionic liquids** *S. Morrissey, I. Beadham, N. Gathergood* Green Chemistry 2009, **DOI:**10.1039/b815566f
- **Hydrogenation in ionic liquids – A review** *S. Morrissey, N. Gathergood* submitted for publication to Green Chemistry
- **Biodegradable ionic liquids: selected synthetic applications** *S. Bouquillon, T. Courant, D. Dean, N. Gathergood, S. Morrissey, B. Pegot, P.J. Scammells, R.D. Singer* Published in the Australian Journal of Chemistry 2007, **60**, 843-847

Table of Contents

Abbreviations

A

acac: acetylacetonate

ACN: acetonitrile

AMP: adenosine monophosphate

ATRP: atom transfer radical polymerization

B

BAC: benzalkonium chloride

benzylmim: 1-benzyl-3-methylimidazolium

BF_4: tetrafluoroborate

BINAP: 2,2'-bis(diphenylphosphino)-1,1'-binaphthyl

bmim: 1-butyl-3-methylimidazolium

bmpyr: 1-butyl-3-methylpyridinium

BOD: biochemical oxygen demand

BP: Bruce Pégot

btfmi: bis(trifluoromethylsulfonyl)imide

C

CIL: chiral ionic liquid

CFU: colony forming unit

COD: cyclooctadiene

COSY: correlation spectroscopy

D

DABCO: 1,4-diazabicyclo[2.2.2]octane

DCM: dichloromethane

dmim: 1-decyl-3-methylimidazolium

dodecylmim: 1-dodecyl-3-methylimidazolium

E

EC: effective concentration

ee: enantiomeric excess

emim: 1-ethyl-3-methylimidazolium

G

GC: gas chromatography

H

HF: hydrofluoric acid

hmim: 1-hexyl-3-methylimidazolium

hmpyr: 1-hexyl-3-methylpyridinium

HPLC: high performance liquid chromatography

I

IC: inhibitory concentration

IL: ionic liquid

IPA: isopropanol

K

K_{ow}: octanol-water partition coefficient

L

LC: lethal concentration

M

MBC: minimum bactericidal concentration

mbpy: 4-methyl-*N*-butyl-pyridinium

MeOH: methanol

MFO: mixed function oxidase

MIC: minimum inhibitory concentration

mim: methylimidazolium

mp: melting point

MS: mass spectrometry

MTBE: methyl tert-butyl ether

N

$N(CN)_2$: dicyanamide

NMR: nuclear magnetic resonance

NSAID: non-steroidal anti-inflammatory

NTf_2: trifluoromethanesulfonimide

O

$OctOSO_3$: octyl sulfate

OECD: organisation for economic cooperation and development

omim: 1-octyl-3-methylimidazolium

ompyr: 1-octyl-3-methylpyridinium

OTf: triflate

P

PF_6: hexafluorophosphate

pmim: 1-pentyl-3-methylimidazolium

psi: pounds per square inch

p-Ts: *para*-toluenesulfonate

Q

QSPR: quantitative structure-property relationship

R

RT: room temperature

S

SAR: structure activity relationship

SbF_6: hexafluoroantimonate

$scCO_2$: supercritical carbon dioxide

T

TBA: tetrabutylammonium

TEA: triethylamine

THF: tetrahydrofuran

tlc: thin layer chromatography

TOC: total organic carbon

TOF: turnover frequency

TON: turnover number

TPPTS: tris(3-sulfophenyl)phosphine

TRISPHAT: tris[tetrachlorobenzene-1,2-bis(olato)] phosphate

U

UCD: University College Dublin

V

VOC: volatile organic compound

Project Aims

- To synthesise and characterise a library of novel non-toxic, biodegradable achiral ionic liquids (ILs) containing the ester functionality in the side-chain of the cation moiety
- To investigate the toxicity and biodegradation properties of the achiral IL library
- To establish the effects of the ester moiety, oxygen-containing side-chain and anion on the toxicity and biodegradability
- To synthesise and characterise a library of novel mandelate and lactate based chiral ILs (CILs) containing the ester functionality
- To investigate the biodegradation properties of the CIL library
- To establish the effects of the ester moiety, side-chain and stereochemistry on the biodegradability of these novel compounds
- To evaluate the differences in both properties and biodegradability between the mandelate and lactate CILs
- To screen the novel achiral ILs as suitable reaction solvents for hydrogenation reactions for a wide variety of substrates
- To enhance the 'green' nature of the ILs by recycling the systems used in the hydrogenation reactions
- To investigate the chemoselectivity of the reactions using the achiral ILs
- To investigate the potential differences in reactions due to the type of achiral IL used as solvent
- To employ the CILs as reaction solvents in the hydrogenation of prochiral substrates
- To test the suitability of the chiral ILs as suitable reaction media for these hydrogenation reactions
- To investigate the potential of the novel chiral solvents as potential asymmetric induction media

1 Literature Review

1.1 General Introduction

Flourishing research in the field of organic chemistry has been one of the factors to lead to the development of multinational pharmaceutical companies. As the demand for drugs has been increasing, so has the scale of manufacturing. Large scale synthesis of innumerable drugs is now widespread. The concern for the welfare of our planet has never been so much to the forefront of everyone's minds as now. The overall ignorance towards issues such as global warming is diminishing. The concept of 'Green Chemistry', to reduce or eliminate the use of hazardous chemicals and the production of perilous chemical waste by designing 'environmentally friendly' substitutes, is therefore a key issue in a contribution to ensuring the existence of our planet for proceeding generations. Large scale synthesis of drugs can lead to the production of mass amounts of harmful waste. The concept of 'Green Chemistry' comprises the attempts to develop new cleaner technologies and methodologies that are less harmful to the environment.

Volatile organic compounds (VOC), due to their high vapour pressure, contribute to the destruction of our atmosphere. Their widespread use in the synthesis of compounds leads to the search for less harmful alternatives. In recent years, Ionic Liquids (ILs) have been considered and successfully utilised as alternatives to these VOCs in fields as diverse as analytical separations[1, 2] and transition metal catalysis.[3] In order to decrease or eliminate the use of harmful VOCs used in organic synthesis, chemists are trying to find suitable alternatives, such as solventless conditions.[4, 5] ILs offer another option in place of the use of these destructive solvents. On account of their negligible vapour pressure, ILs pose less of a threat to the atmosphere than VOCs as this low volatility eliminates a pathway for release into the environment.

The first recorded observation of an IL occurred in the mid 19th century when a separate 'red oil' phase formed during Friedel-Crafts reactions.[6] This red oil was only however deemed to be a salt when the use of NMR spectroscopy became widespread, identifying the salt to be a stable intermediate complex formed during Friedel-Crafts reactions.[7] Synthesis of the first IL transpired shortly after, at the beginning of the 20th century. Ethylammonium nitrate $[EtNH_3][NO_3]$ (**1**) was found to have a melting point of only 12 ºC.[8] Although widespread interest was slow to take off, in recent years the number of papers published on ILs has been steadily accelerating.[9, 10] The remarkably interesting

properties of ILs stem naturally from the fact that these salts are liquids at or close to RT (room temperature). Most ILs are composed of a large bulky unsymmetrical cation, and a smaller evenly shaped anion (Figure 1.1).

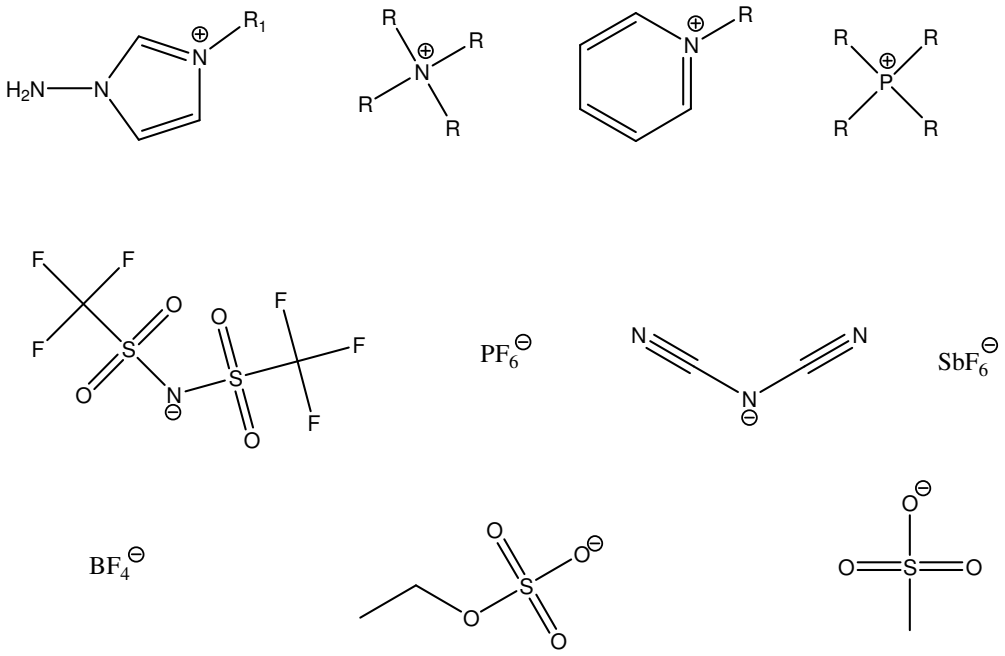


Figure 1.1 Cation and anion examples used frequently in ILs

Considering the composition of ILs, they are not able to pack as well as common salts such as sodium chloride. This inability to form efficient ion-ion packing reduces electrostatic interactions and renders ILs with reduced lattice energies. The diffuse charge found in the unsymmetrical cation coupled with the weakly coordinating anion reduces coulombic interactions. These two factors, namely weak electrostatic forces and delocalised diffuse charge in the anion, lead to ILs with low melting points. It is due to this desirable property that interest in ILs is growing. The solubility of ILs in various solvents can be regulated by choosing a specific anion or cation, the commonly used $[PF_6]$ ILs being hydrophobic, with the $[BF_4]$ salts being hydrophilic. The ability to tune the IL for a particular use, together with their negligible vapour pressures, low melting points, and the fact that they can be reused, are some of the reasons why ILs have this alluring nature. Many ILs synthesised to date have been based on the imidazolium moiety as cation, with weakly coordinating species, such as $[BF_4]$ and $[PF_6]$, dominating the choice of anion. The discovery that the aforementioned ILs can liberate the highly corrosive acid hydrofluoric acid (HF), has however, recently been becoming a deterrent in choosing these inorganic perfluorinated anions. Synthesis of ILs is often quite straightforward, generally the first step being the formation of the cation, which is then

followed by an anion exchange. Cation formation can be performed by protonation of a suitable basic starting material with an acid, or, quaternization of an amine or related starting material, for example a phosphine. Anion metathesis proceeds, in most cases, by the reaction of the halide salt, the precursor to the desired IL, with an inorganic salt consisting of the desired anion. Mostly, the unwanted inorganic salts from these reactions are insoluble in the reaction solvent and thus simple filtration allows the desired IL to be obtained.

Due to the vast possible combinations of cations and anions, the challenge surrounding IL formation is not only the design and synthesis of a safer, more environmentally friendly substance. The IL should merit its replacement for a more harmful alternative (e.g. VOC) in a process by enhancing the procedure by means of, for example, increased yield/separation, decreased formation of side products or higher enantioselectivity.

Most researchers working in the field of 'Green Chemistry' will be familiar with the 12 basic principles devised by Clark and Macquarrie in 2002.[11] The work presented herein can be related to many of the principles.

Principle 3. *Less hazardous chemical use. Synthetic methods should be designed to use and generate substances that possess little or no toxicity to the environment and public at large.* Many of the novel ILs presented in this thesis are non-toxic to bacteria.

Principle 4. *Design for safer chemicals. Chemical products should be designed so that they not only perform their designed function but are also less toxic in the short and long terms.* The ester functionality present in these ILs increases the biodegradability, and in many cases does not increase the melting point, thus the ILs can be utilised as reaction solvents at close to ambient temperature.

Principle 5. *Safer solvents and auxiliaries. The use of auxiliary substances such as solvent or separation agents should not be used whenever possible. If their use cannot be avoided, they should be used as mildly or innocuously as possible.* Again, the ILs designed herein are non-toxic, thus could be considered as a 'mild' alternative to a harmful VOC.

Principle 9. *Catalysis. Catalytic reagents are superior to stoichiometric reagents. The use of heterogeneous catalysts has several advantages over the use of homogeneous or liquid catalysts. Use of oxidation catalyst and air is better than using stoichiometric quantities of oxidising agents.* For use in the hydrogenation of achiral substrates, a palladium heterogeneous catalyst was used. It was also immobilised in the IL thus facilitating the recycling of experiments, an inherently 'green' process.

Principle 10. *Design for degradation. Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment. A life-cycle analysis (beginning to end) will help in understanding its persistence in nature.* Many of the ILs comprising the ester functionality and the [$OctOSO_3$] anion are shown to surpass the 60 % pass rate for biodegradability required for the OECD 301B test.

Principle 12. *Inherently safer chemistry for accident prevention. Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accident, including releases, storage of toxic chemicals, explosions, and fires.* Due to their negligible vapour pressure, ILs in general are non-flammable, therefore limiting them as a source of ignition of fires and explosions.

1.2 Toxicity and Biodegradability of ILs

1.2.1 Introduction

Though ILs are classed as 'green solvents' mainly due to their negligible vapour pressure, consideration for their end of life factors should be of equivalent importance in this classification. To satisfy the requirements of being 'green solvents', it is desirable for ILs not to persist in the environment and should be non-toxic or of limited toxicity to the environment and life within. If ILs are to be used in industry for large scale synthesis, their disposal could be detrimental to the environment if their toxicity and biodegradability in the environment are not studied beforehand. Even though ILs may be benign to the atmosphere compared to toxic VOC fumes, their effect on aquatic and terrestrial life is still of key importance and a detailed study is paramount.

1.2.2 History of Toxicity of ILs

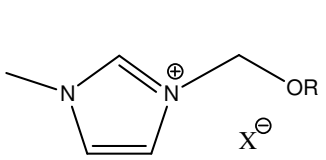
A brief history of ILs was documented by Zhao *et al.* in their review[12] and an overview of toxicological data of ILs was published by Ranke *et al.*.[13] Laboratory tests have been used by various groups, each focusing on key parts of a system. Toxicological and ecotoxicological data has been gathered by using test systems based on different biological complexity levels. Toxicity and antimicrobial studies have been performed on a range of bacteria and fungi, acute toxicity studies have been carried out on fish, growth inhibition studies have been carried out on algae, terrestrial plants have been tested for growth and these will be presented in the following sections.

The organisms studied range from bacteria and fungi, to higher organisms such as the soil nematode and the freshwater snail to terrestrial plants. The ILs studied are mainly of imidazolium and pyridinium classes, with alkyl or alkoxy side chains, containing [Br], [Cl], [PF_6] or [BF_4] anions. Preliminary studies on the effects of ILs on mammalian cell lines have also been conducted, as well as enzymatic studies.

Collected results show the toxicity of ILs increase with increasing alkyl chain length. The similarity of ILs to cationic surfactants entails that the toxicity of ILs may be due to the increasing membrane permeability. Increasing chain length could thus lead polar narcosis. [14, 15, 16]

1.2.2.1 Toxicity testing using bacterial species

The antimicrobial activities of a range of methylimidazolium ILs containing an alkoxymethyl side chain (Figure 1.2) ranging from C_3 – C_{16} **2** - **15** with anions [Cl] **a**, [BF_4] **b** and [PF_6] **c** were measured by Pernak *et al.*.[17] Cocci (*Micrococcus luteus*, *Staphylococcus epidermidis*, *Staphylococcus* aureus, *Staphylococcus aureus MRSA*, *Enterococcus hirae*), rods (*Escherichia coli, Proteus vulgaris, Klebsiella pneumoniae, Pseudomonas aeruginosa*) and fungi (*Candida albicans, Rhodotorula rubra*) were tested. The minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) values were noted and compared to the commercially available benzalkonium chloride (BAC) **16**. The authors showed all ILs with a side chain greater than C_6 to be active against all organisms, and the activity to be dependent on side chain length and not the anion. The most active ILs against rods and cocci were those with the side-chain of C_{10} **9**, C_{11} **10**, C_{12} **11** and C_{14} **13**; C_{12} **11** being the most active of these. All three salts containing C_{12} in the alkoxy side chain approached the activity of BAC.

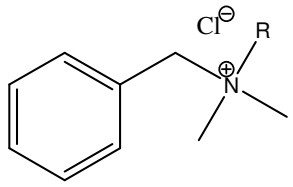


3-alkoxymethyl-1-methylimidazolium salt

R: C_3-C_{16} **2** - **15**

X: [Cl], [BF_4], [PF_6]

a **b** **c**



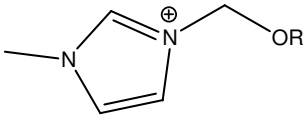
BAC: benzalkonium chloride

R: C_8H_{17}-$C_{18}H_{37}$

16

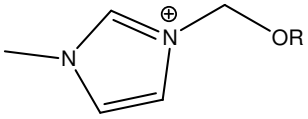
Figure 1.2 Imidazolium ILs containing alkoxy side-chain

Results obtained from two cocci strains and three strains of rods can be seen in Table 1.1 and Table 1.2. The MIC values obtained for BAC ranged from as low as 7 - 11 μM against strains *S. aureus*, *E. hirae*, *E. coli* and *K. pneumoniae* to 54 μM against *P. aeruginosa*.



	Staphylococcus aureus MIC (μM)			*E. hirae* MIC (μM)		
R	[Cl] (**a**)	[BF_4] (**b**)	[PF_6] (**c**)	[Cl] (**a**)	[BF_4] (**b**)	[PF_6] (**c**)
C_3H_7 **2**	> 8600	> 7000	> 5850	> 8600	> 7000	> 5850
C_4H_9 **3**	> 8600	> 7000	> 5850	> 8600	> 7000	> 5850
C_5H_{11} **4**	> 8600	> 7000	> 5850	> 8600	> 7000	> 5850
C_6H_{13} **5**	4300	7000	2900	8600	3500	2900
C_7H_{15} **6**	500	840	2800	8100	3360	2800
C_8H_{17} **7**	480	800	1350	1900	1600	2700
C_9H_{19} **8**	228	384	650	228	384	330
$C_{10}H_{21}$ **9**	54	92	160	108	92	630
$C_{11}H_{23}$ **10**	52	22	19	103	88	152
$C_{12}H_{25}$ **11**	25	21	18	99	95	37

Table 1.1 MIC values obtained against cocci strains



	E. coli MIC (μM)			*K. pneumoniae* MIC (μM)			*P. aeruginosa* MIC (μM)		
R	[Cl] (**a**)	[BF_4] (**b**)	[PF_6] (**c**)	[Cl] (**a**)	[BF_4] (**b**)	[PF_6] (**c**)	[Cl] (**a**)	[BF_4] (**b**)	[PF_6] (**c**)
C_3H_7 **2**	> 8600	> 7000	> 5850	> 8600	> 7000	> 5850	> 8600	> 7000	> 5850
C_4H_9 **3**	> 8600	> 7000	> 5850	> 8600	> 7000	> 5850	> 8600	> 7000	> 5850
C_5H_{11} **4**	> 8600	> 7000	> 5850	> 8600	> 7000	> 5850	> 8600	> 7000	> 5850
C_6H_{13} **5**	8600	7000	5850	8600	7000	5850	8600	7000	5850
C_7H_{15} **6**	8100	6700	5600	8100	6700	5600	4060	6700	5600
C_8H_{17} **7**	3800	3200	2700	3800	1600	2700	3800	3200	2700
C_9H_{19} **8**	1820	1540	1300	1820	3070	2600	1820	1540	2600
$C_{10}H_{21}$ **9**	433	368	1250	433	368	630	867	1471	1250
$C_{11}H_{23}$ **10**	413	177	607	207	177	152	826	707	1214
$C_{12}H_{25}$ **11**	99	170	73	197	170	147	395	340	587
$C_{14}H_{29}$ **12**	181	316	138	181	158	138	726	632	1100
$C_{16}H_{33}$ **13**	671	-	-	168	-	-	2680	-	-

Table 1.2 MIC values obtained against three strains of rods

Pernak *et al.* synthesized and investigated physical properties and biological activities of a series of DL- and L- alkyl (**17/18**) and alkoxy (**19/20**) imidazolium lactate ILs[18] (Figure 1.3). The side chain lengths investigated ranged from C_1 to C_{12}. 5 strains of rods (*Escherichia coli, Proteus vulgaris, Klebsiella pneumoniae, Pseudomonas aeruginosa, Serratia marcescens*), 5 strains of cocci (*Micrococcus luteus, Staphylococcus epidermis, Staphylococcus aureus, Staphylococcus aureus MRSA, Enterococcus hirae*) and 2 strains of fungi (*Candida albicans, Rhodotorula rubra*) were subjected to a selection of the lactate ILs. In general, the L-lactates (**18** and **20)** showed lower MIC values than the DL- lactates (**17** and **19**), with the lowest values seen for L - lactates with 11 or 12 carbons in the side chain, the most inhibitory being the C_{11} alkoxy L-lactate IL (**20h**). The lowest MBC values for cocci was noted for DL- lactates containing 12 carbons and L-lactates containing 11 carbons. Compared to the MIC and MBC values of BAC, it

was shown that the L-lactates with the longest chains exhibited similar activity. Lactates C_1 - C_5 generally proved to be inactive.

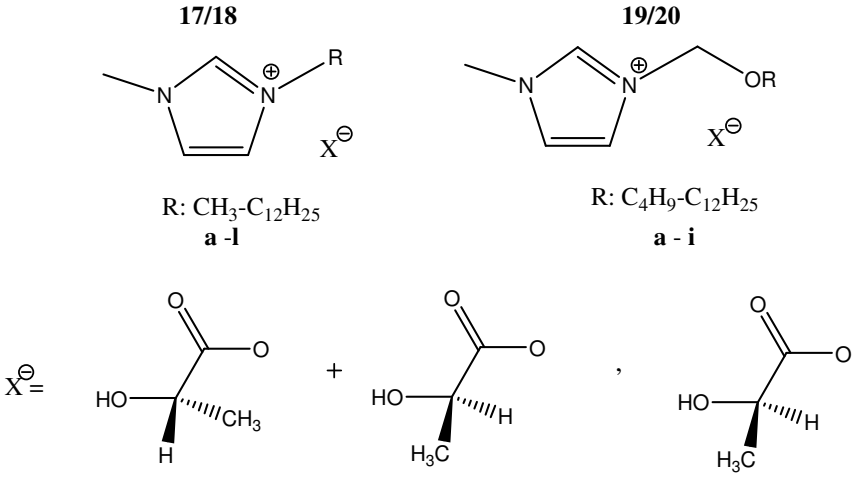
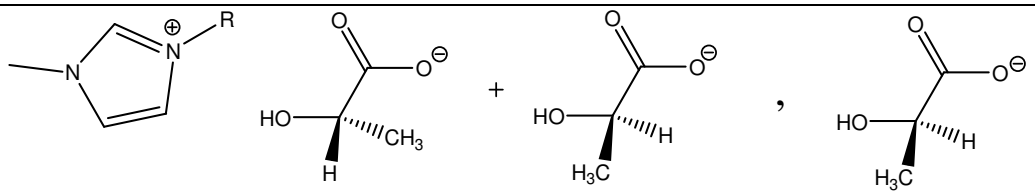


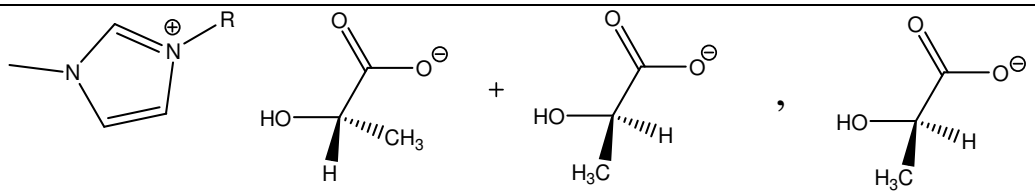
Figure 1.3 Lactate ILs

Results obtained from two strains of cocci and three strains or rods can be viewed in Table 1.3 and Table 1.4 for the alkylimidazolium ILs (**17/18**) and Table 1.5 and Table 1.6 for the alkoxy derivatives (**19/20**). MIC values obtained for BAC ranged from 2.8 – 11 μM for *S. aureus*, *E. hirae*, *E. coli* and *K. pneumoniae* and was 175 μM for *P. aeruginosa*.



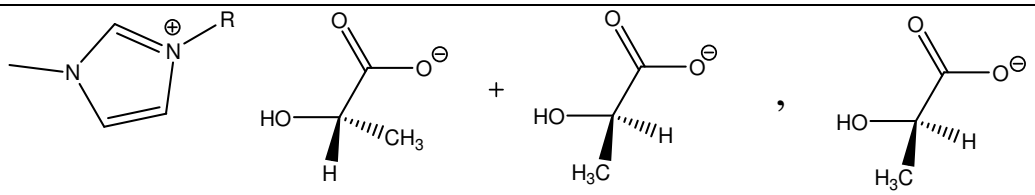
	DL (**17**)		L (**18**)	
R	*S. aureus* MIC (μM)	*E. hirae* MIC (μM)	*S. aureus* MIC (μM)	*E. hirae* MIC (μM)
CH_3 **a**	> 5814	> 5814	> 5814	> 5814
C_2H_5 **b**	> 5814	> 5814	> 5814	> 5814
C_3H_7 **c**	> 5814	> 5814	> 5814	> 5814
C_4H_9 **d**	> 5814	> 5814	> 5814	> 5814
C_5H_{11} **e**	> 5814	> 5814	> 5814	> 5814
C_6H_{13} **f**	> 4132	> 4132	4132	> 4132
C_7H_{15} **g**	> 3906	> 3906	1953	3906
C_8H_{17} **h**	926	1852	926	1852
C_9H_{19} **i**	110	440	110	220
$C_{10}H_{21}$ **j**	105	209	52	105
$C_{11}H_{23}$ **k**	75	100	25	50
$C_{12}H_{25}$ **l**	144	96	24	48

Table 1.3 MIC values obtained using alkylimidazolium ILs against cocci



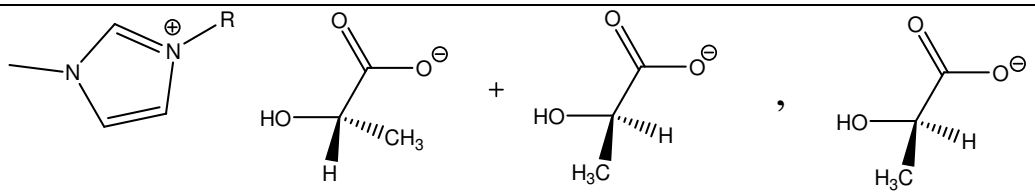
	DL (**17**)			L (**18**)		
R	*E. coli* MIC (μM)	*K. pneumoniae* MIC (μM)	*P. aeruginosa* MIC (μM)	*E. coli* MIC (μM)	*K. pneumoniae* MIC (μM)	*P. aeruginosa* MIC (μM)
CH_3 **a**	> 5814	> 5814	> 5814	> 5814	> 5814	> 5814
C_2H_5 **b**	> 5814	> 5814	> 5814	> 5814	> 5814	> 5814
C_3H_7 **c**	> 5814	> 5814	> 5814	> 5814	> 5814	> 5814
C_4H_9 **d**	> 5814	> 5814	> 5814	> 5814	> 5814	> 5814
C_5H_{11} **e**	> 5814	> 5814	> 5814	> 5814	> 5814	> 5814
C_6H_{13} **f**	2066	2066	4132	2066	2066	4132
C_7H_{15} **g**	1953	1953	> 3906	977	1953	3906
C_8H_{17} **h**	463	463	1852	463	463	3704
C_9H_{19} **i**	220	220	1761	220	220	880
$C_{10}H_{21}$ **j**	209	209	1678	105	209	839
$C_{11}H_{23}$ **k**	200	200	3205	50	100	802
$C_{12}H_{25}$ **l**	192	192	3067	48	96	1534

Table 1.4 MIC values obtained using alkylimidazolium ILs against rods



	DL (**19**)		L (**20**)	
R	*S. aureus* MIC (μM)	*E. hirae* MIC (μM)	*S. aureus* MIC (μM)	*E. hirae* MIC (μM)
C_4H_9 **a**	> 4098	> 4098	4098	> 4098
C_5H_{11} **b**	3876	> 3876	> 3876	> 3876
C_6H_{13} **c**	3676	> 3676	3676	3676
C_7H_{15} **d**	1748	> 3497	874	1748
C_8H_{17} **e**	417	1667	417	1667
C_9H_{19} **f**	498	1592	199	398
$C_{10}H_{21}$ **g**	380	1524	47.6	95
$C_{11}H_{23}$ **h**	183	183	11.4	45.6
$C_{12}H_{25}$ **i**	88	176	10.9	44

Table 1.5 MIC values obtained using alkoxyimidazolium ILs against cocci



	DL (**19**)			L (**20**)		
R	*E. coli* MIC (μM)	*K. pneumoniae* MIC (μM)	*P. aeruginosa* MIC (μM)	*E. coli* MIC (μM)	*K. pneumoniae* MIC (μM)	*P. aeruginosa* MIC (μM)
C_4H_9 **a**	2049	> 4098	> 4098	4098	2049	> 4098
C_5H_{11} **b**	969	1938	> 3876	1938	1938	> 3876
C_6H_{13} **c**	459	229	3676	919	459	> 3676
C_7H_{15} **d**	219	219	3497	437	219	3497
C_8H_{17} **e**	104	208	3333	208	208	1667
C_9H_{19} **f**	49	199	3185	199	199	1592
$C_{10}H_{21}$ **g**	95	190	3049	95	190	3049
$C_{11}H_{23}$ **h**	92	183	2924	183	92	> 2924
$C_{12}H_{25}$ **i**	350	176	2809	88	88	> 2809

Table 1.6 MIC values obtained using alkoxyimidazolium ILs against rods

Toxicity of imidazolium and pyridinium ILs with varying side-chain length was measured in the bioluminescent marine bacteria, *Vibrio fischeri*, a decrease in light output signifying an increase in toxicity.[19] The antimicrobial effect of these ILs was also determined using five different microorganisms from a variety of physiological and respiratory capabilities (*Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis*, *Pseudomonas fluorescens* and *Saccharomyces cerevisiae*). Toxicity results showed an increasing toxicity with an increase in the alkyl chain length. The hexyl and octyl side chains were shown to be more toxic than commonly used organic solvents, with the butyl side chain being the same as some of the less toxic solvents. For the pyridinium IL, toxicity increased with an increase in the number of substituents on the ring of the cationic species. Pyridinium ILs could not be deemed as more or less toxic than their imidazolium counterparts as can be seen from the fact that [bmim][Br] (**21**) is less toxic than [bmpyr][Br] (**22**), [hmim][Br] (**23**) is more toxic than [hmpyr][Br] (**24**) and [omim][Br] (**25**) is of approximately equal toxicity as [ompyr][Br] (**26**). The

antimicrobial activity for all organisms was shown to increase with increasing alkyl chain length. The octyl containing side chain was shown to be the most effective at inhibiting colony formation, followed by hexyl, with butyl not showing much difference to the buffer. [Omim][Br] (**25**) and [ompyr][Br] (**26**) were shown to be the most effective antimicrobial ILs tested in the study. All ILs were shown to be most inhibitory to *Bacillus subtilis*. *Escherichia coli* and *Pseudomonas fluorescens* were significantly affected by all ILs and *Staphylococcus aureus* and *Saccharomyces cerevisiae* were the least affected. Since the same trend of increasing toxicity with increasing alkyl chain length can be seen for all organisms, the authors suggest that the toxicity may be related to a cellular structure or process that is common in all the organisms studied.

Vibrio fischeri is a commonly used organism to measure toxicity as the acute bioluminescence inhibition assay (DIN EN ISO 11348) is widely used in Europe and therefore a variety of EC values are available for comparison. Using these organisms, increasing alkyl chain length of ILs was found to increase toxicity.[15, 16, 20] Another luminescent bacteria, *Photobacterium phosphoreum* (Figure 1.4), was used by Gathergood *et al.*[21] which again displayed the same trend.

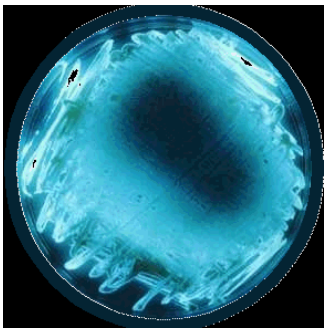


Figure 1.4 Culture showing *Photobacterium phosphoreum* [22]

While studying a range of aquatic organisms including *Vibrio fischeri*, Stolte *et al.*[23] investigated the effects of IL head groups, functionalised side chains and anions of ILs on toxicity. They found the halide anions (chloride and bromide) did not exhibit an intrinsic effect on toxicity, however the [NTf_2] anion was found to display toxicity. Together with demonstrating the increasing toxicity with increasing side-chain length effect, they found the introduction of polar groups to the side chain of the IL to decrease toxicity.

While investigating the possibility of using imidazolium based ILs for the extractive fermentation of lactate, Matsumoto *et al.* investigated the toxicity of these ILs on the

lactic acid producing bacterium *Lactobacillus rhamnosus* NBRC 3863.[24] The ILs tested were [bmim] (**27**), [hmim] (**28**) and [omim][PF_6] (**29**) and batch test culture experiments were performed to investigate the toxicity. The results of these experiments were based on the activity of the bacterium. The amount of glucose consumed was measured, along with the colony forming unit (CFU) values. CFU values measured the survival rate of *Lactobacillus rhamnosus* and these corresponded to the glucose consumption, thus indicating that the viable cells produced lactate. The overall results showed that this bacterium survived in all ILs measured, but demonstrated a low activity. These results were compared with toluene, for which almost no survival of the bacteria could be noted. There was little difference exhibited in results shown for the three varying side chain lengths, with butyl and hexyl being approximately equal and showing slightly more activity than octyl. To examine the suitability of ILs as a replacement for organic solvents in *in situ* extractive fermentation of lactic acid, Matsumoto *et al.* investigated the toxicity of the same imidazolium ILs used in their previous test on a series of nine bacteria (*Lactobacillus Rhamnosus, Lactobacillus Homohiochi* (NRIC 0119 and 1815), *Lactobacillus Fructivorans* (NRIC 0224 and 1814), *Lactobacillus Delbruekii*, *Lactobacillus Pentosaceus, Leuconostoc Fallax, Bacillus coagulans*).[25] The ability of the bacteria to produce lactic acid was a measure of the toxicity. The results showed all bacteria produce lactic acid in the presence of the ILs, with *Lactobacillus delbruekii* showing the highest concentrations produced. The ability to produce the acid was seen to decrease upon increasing alkyl chain length.

Docherty *et al.*[26] performed the first Ames test on ILs. The Ames test is a method of elucidating the mutagenicity of a compound. 10 bromide salts were tested based on the popular imidazolium, pyridinium and quaternary ammonium cations. The strains of *Salmonella typhimurium* bacteria used were the histidine-requiring TA98 and TA100. The ability of the IL to cause mutation in these bacteria was measured. After interaction with mutagens, these strains of bacteria revert to histidine independent strains. This rate of reversion is used as a measure of the mutagenicity of the tested compound. The ILs were tested over a broad concentration range (0.01 – 20 mg per plate) however none of the ILs met the United States Environmental Protection Agency (US EPA) criteria for mutagenicity. Some ILs did nevertheless show potential to be mutagenic at high doses. The imidazolium based ILs were the culprits of this mutagenic effect however the authors advise further work to be carried out for these results to be conclusive.

1.2.2.2 Toxicity testing using aquatic eukaryotes (*Daphnia magna*)

The aquatic eukaryotes, *Daphnia Magna* (Figure 1.5) are popular for the investigation of IL toxicity.

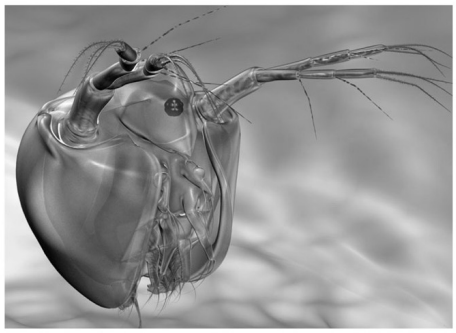


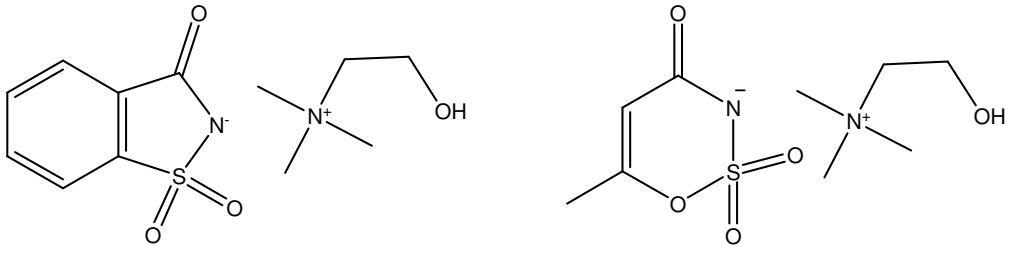
Figure 1.5 *Daphnia Magna*[12]

Increasing alkyl chain length was again found to increase toxicity in imidazolium ILs.[21, 27] The acute and chronic toxicity of imidazolium based ILs was measured against these organisms.[28] The ILs used were [bmim][Br] (**21**), [Cl] (**30**), [PF_6] (**29**) and [BF_4] (**31**). These ILs were compared to the corresponding sodium salts containing the same anion. It was concluded that the cationic species of the IL affected toxicity. LC_{50} values were an order of magnitude lower for all ILs containing the imidazolium moiety compared to their sodium analogues. Concerning the acute toxicity study, the most toxic species was found to be [bmim][Br] (**21**) (LC_{50}: 8.03 mg L^{-1}), with $NaPF_6$ being the least toxic (LC_{50}: 9344.81 mg L^{-1}). The reproductive output of *Daphnia magna* was negatively affected regarding all the imidazolium ILs. In order to judge the relative toxicity of these ILs, the authors compared their LC_{50} values to those of commonly used organic solvents. It was shown that the ILs demonstrated LC_{50} approximately equal to those of phenol (LC_{50}: 10-17 mg L^{-1}), tetrachloromethane (LC_{50}: 35 mg L^{-1}) and trichlormethane (LC_{50}: 29 mg L^{-1}), however the values of the ILs were lower than benzene (LC_{50}: 356-620 mg L^{-1}), methanol (LC_{50}: 3289 mg L^{-1}) and acetonitrile (LC_{50}: 3600 mg L^{-1}). The authors also note these particular ILs to be less toxic than chlorine (LC_{50}: 0.12-0.15 mg L^{-1}) and ammonia (LC_{50}: 2.90-6.93 mg L^{-1}). It is stated that the mechanism of toxicity to *Daphnia magna* is unknown, but based on previous studies[29-31] they propose enzyme inhibition, disruption of membrane permeability or structural DNA damage as possible modes of action.

A range of ILs containing imidazolium, pyridinium and ammonium cations were tested for toxicity against two aquatic organisms (*Vibrio fischeri* and *Daphnia magna*) in order

to create quantitative structure property relationship models, to be thus used to predict toxicity.[15] Neonates of *Daphnia magna* less than 24 hours old were used in a 48 hour acute toxicity bioassay to measure the toxicity of the ILs on this organism. The authors used the results obtained to build a predictive toxicity model based upon QSPR modelling in order to be able to design ILs with limited toxicity. This QSPR modelling is based on the idea that for a given compound, chemical structure determines physical properties. The experimental results show that the toxicity increases with alkyl chain length of the cation, and that the corresponding salts used to synthesise the IL, i.e. NaBr, are less toxic than the ILs. This indicates the negligible effect of the anionic species on toxicity. The results also show that ILs containing the imidazolium and pyridinium cations are more toxic than those containing the quaternary ammonium species. The predictive results based on these experimental results indicated again increasing alkyl chain length to increase toxicity. Also predicted was the fact that the toxicity would increase with an increase in the number of nitrogen atoms on the cationic species. The addition of methyl groups to the aromatic ring of the cation is predicted to decrease toxicity and monoatomic anions, i.e. Br, should be less toxic than anions containing regions of positive charge, i.e. [NTf_2]. The imidazolium cation was predicted to be more toxic than the pyridinium, which in turn was predicted to be more toxic than the ammonium (cation toxicity: imidazolium > pyridinium > ammonium).

Nockemann *et al.*[32] investigated the ecotoxicity of their choline saccharinate (**32**) and acesulfamate (**33**) ILs (Figure 1.6).



choline saccharinate
32

choline acesulfamate
33

Figure 1.6 Choline saccarinate and choline acesulfamate ILs

Choline chloride is used as an additive in chicken feed, and saccharinate and acesulfamate are salts of artificial sweeteners. The authors suggest these ILs to be of 'food grade' thus should display limited toxicity. Indeed these two ILs displayed toxicity to *Daphnia magna* two orders of magnitude less than common imidazolium and pyridinium ILs.

1.2.2.3 Toxicity testing using algal species

The toxicity of imidazolium ILs was investigated on two taxonomically different algal species, *Oocystis submarina* and *Cyclotella meneghiniana*.[33] The growth inhibition of these species was measured in relation to [emim] (**34**), [bmim] (**32**), [hmim] (**35**) and [benzylmim][BF_4] (**36**). As was demonstrated here, diatoms (*Cyclotella meneghiniana*) are normally used when investigating marine alga, as they are the most sensitive to organic compounds. Growth inhibition was measured over 3 concentration values of each IL. For *Oocystis submarina*, the results show the same pattern of cell growth inhibition for all the ILs tested. The two lowest concentrations showed cell growth to be inhibited initially and then resume within the time frame of the experiment, showing the alga to acclimatize to the conditions of the IL. The highest concentration however showed the growth to be inhibited completely for the duration of the experiment. In the case of *Oocystis submarina*, growth inhibition was at its greatest for the shortest alkyl chain length, [emim][BF_4] (**34**). For *Cyclotella meneghiniana*, growth inhibition was observed for all concentrations of IL throughout the experiment.

The unicellular freshwater alga, *Pseudokirchneriella subcapitata* (formerly known as *Selenastrum capricornutum*), was used as test organism for measuring the toxicity of ILs.[27, 34] Cho *et al.*[34] examined the anion effect of imidazolium ILs on the toxicity. Their results showed the [SbF_6] anion to be most toxic, with the other anions tested decreasing in toxicity in the order [PF_6] > [BF_4] > [CF_3SO_3] > [$C_8H_{18}OSO_3$] > [Br] ≈ [Cl]. Cho *et al.*[35] also investigated the side-chain effect on the toxicity using the same organism. Imidazolium bromide salts with side chain lengths, [omim], [hmim], [bmim], [pmim], were found to display decreasing toxicity with decreasing chain length. Using the same alga as an indicator for toxicity, Pham *et al.*[36] found the same trend of decreasing toxicity with decreasing alkyl chain length. They also found the pyridinium ILs tested to be more toxic than their imidazolium counterparts. In comparison with organic solvents, most of the ILs they tested were more toxic than methanol, DMF and 2-propanol. The same trend of decreasing toxicity with decreasing alkyl chain length was found by Kulacki and Lamberti[37] using [bmim] (**21**), [hmim] (**23**) and [omim] bromide (**25**) ILs. They examined the non-motile *Scenedesmus quadricauda* and the mobile *Chlamydomonas reinhardtii* freshwater algae in nutrient-rich media and low-nutrient groundwater to uncover if these parameters altered toxicity. The same trend was however observed with both algae in both media tested. *Scenedesmus vacuolatus*

was used as a test organism for IL toxicity by Stolte *et al.*[38] and Matzke *et al.*.[39] The side-chain effect was presented in both studies.

1.2.2.4 Toxicity studies using plants

Jastorff *et al.* studied the ecotoxicity and the genotoxicity of [BF_4] ILs.[40] Together with their studies using higher plants, they also used the WST cell viability assays to determine the effects that the anion and headgroup have on toxicity. Two higher plants (Figure 1.7), namely the floating aquatic organism lesser duckweed (*Lemna minor*) and the fast growing terrestrial plant, garden cress (*Lepidium sativum*), were used to study the toxicity of the ILs [bmim] (**31**) and [omim][BF_4] (**37**).

Figure 1.7 Lesser duckweed[41] and garden cress[42]

Both tests showed [omim][BF_4] (**37**) to be more toxic than [bmim][BF_4] (**31**). In the case of *L. minor*, the number of foliaceous fronds produced in comparison to a control plant indicated the toxicity level. [Omim][BF_4] (**37**) showed an 87 % reduction in growth at a concentration of 10 $mgkg^{-1}$, while the [bmim] IL showed no reduction even at an IL concentration of 100 $mgkg^{-1}$. The effect of the ILs on *Lepidium sativum* was monitored by the number of seedlings produced by the plant. At a concentration of 100 $mgkg^{-1}$, [omim][BF_4] (**37**) significantly reduced the number of seedlings produced, while a significant effect was only noted for [bmim] at a concentration of 1000 $mgkg^{-1}$. Stolte *et al.*[38] and Matzke *et al.*[39] studied the toxic effects of ILs on *Lemna minor*, wheat (*Triticum aestivum*) and *Lepidium sativum*.The side-chain length effect was observed in both cases.

Balczewski *et al.*[43] synthesised novel CILs and tested them for toxicity using the superior plants, Spring Barley (*Hordeum vulgare*) and Common Radish (*Raphanus Sativus*). A selection of their ILs was toxic and toxicity was found to be concentration-dependent.

1.2.2.5 Toxicity testing using mammalian cell lines

The toxicity of imidazolium based ILs was tested on the luminescent bacteria, *Vibrio fischeri* and rat cell lines C_6 (glioma cells) and IPC 81 (leukaemia cells).[16] These cell lines were chosen to obtain information about the effect of the ILs on two physiologically different areas, namely the haematopoietic system and the central nervous system. The effects of increasing chain length of the R_1 (methyl and ethyl) and R_2 (C_3 – C_6) position on the imidazolium moiety was investigated, together with the effect of the anionic species on the cell viability assays.

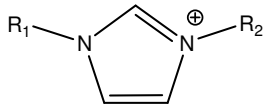


Figure 1.8 R_1 and R_2 positions on imidazolium cation

The anions chosen were the popular [PF_6] and [BF_4], which were then compared to [Br], [Cl] and [*p*TS] anions. It was shown that toxicity increased with increasing alkyl chain length, both for the R_1 and R_2 positions, for each system tested. The authors propose this effect to be due to the increased lipophilicity and therefore increased ease of permeability. Their results showed an increase in toxicity when the length of the R_1 side chain was increased in comparison with increasing length of the R_2 side chain. Overall no effect of the different anion on the test systems could be noted therefore rendering the cationic species the determining factor for toxicity. A comparison with the widely used organic solvents, methanol, acetone, acetonitrile and MTBE, showed the ILs to be more toxic than all the organic solvents except for the case of MTBE, which showed similar toxicity to the ILs studied in the *Vibrio fischeri* assay.

Mammalian blood cells were used to test the genotoxicity of two ILs, [bmim] (**31**) and [dmim][BF_4] (**38**), using the SCE (sister chromatid exchange) assay.[40] [Bmim][BF_4] (**31**) was shown to have no genotoxic effects within the given concentration range, while [dmim][BF_4] (**38**) showed a dose dependent trend within half of this concentration range. The group also mention their preliminary finding on the anion effects of ILs on toxicity. A significant difference in toxicity between the [BF_4] and [NTf_2] anion was shown. Also, significant differences in toxicity between various headgroups of the ILs, namely between [bmpyr] and [bmim], and [bmpy] and [bmim] were evident. Finally, this group theoretically formulated the possible metabolites of the [bmim] and [omim] cations (Figure 1.9 and Figure 1.10). The most probable metabolites were synthesised and their toxicity was measured, using the WST cell viability assay, to

compare their toxicity to the parent IL. As can be seen from Figure 1.9 and Figure 1.10, all metabolites were shown to be less toxic than the parent IL, with the introduction of polar groups to the side chain further reducing their toxic effect.

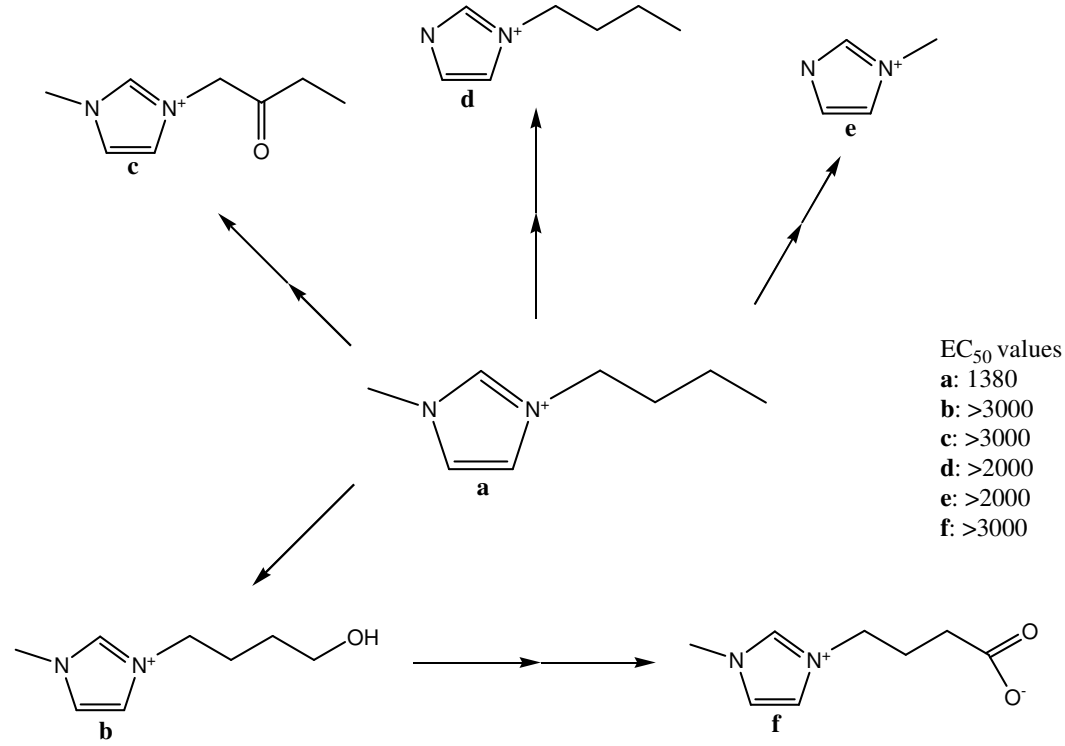


Figure 1.9 Cytotoxicity of [bmim] cation in comparison to some of its hypothetical metabolites

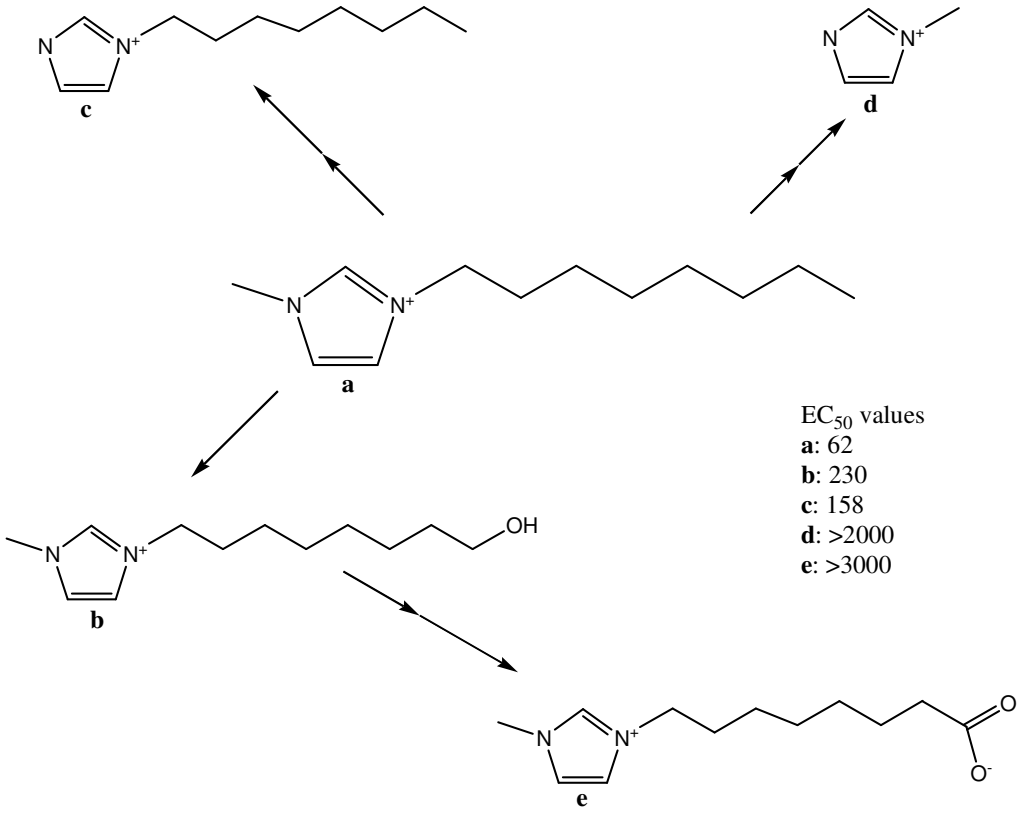


Figure 1.10 Cytotoxicity of [omim] cation in comparison to some of its hypothetical metabolites

Progressing from this work, Stolte *et al.*[44] embarked on a study investigating the anion effects of ILs on cytotoxicity using the WST-1 cell viability assay, this time however using the IPC-81 rat leukaemia cell line. Out of 27 commercially available anions tested, only 10 displayed cytotoxicity (Figure 1.11).

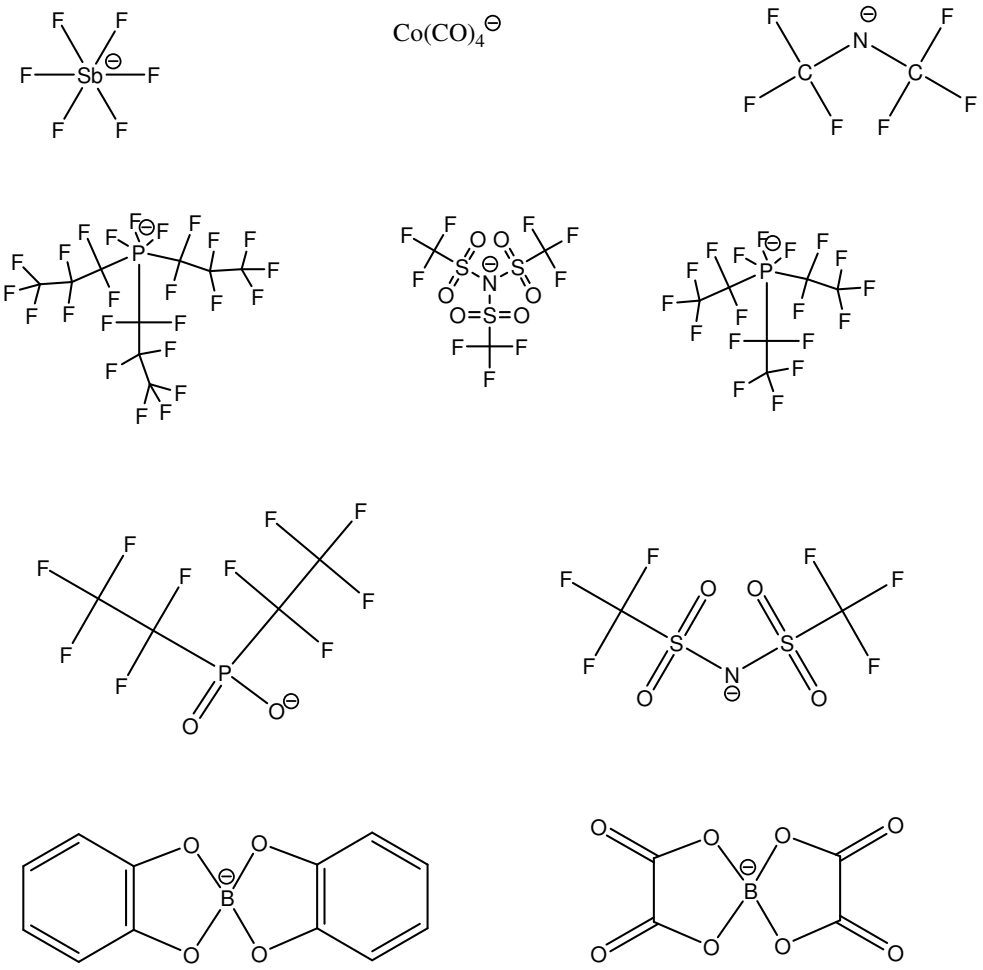


Figure 1.11 Anions that tested positive for cytotocicity

They tested a concentration range of 1µM – 1mM, and if no effect was evident, the upper range was extended to 20 mM. EC_{50} values were used as a measure of the cytotoxicity. As sodium or lithium chloride showed no cytotoxic effects within this range, the cations of these salts were used for the cytotoxicity study of the intrinsic effects of the anionic moiety of the IL. In order to ascertain an effect of the anion combined with typical IL cations, the anions were combined with the widely used [mim] cation with side chain lengths ranging from C_2 to C_6. The tests revealed that the combination of the anions with these cationic headgroups did indeed increase the toxicitiy results obtained.

Stolte *et al.*[38] again used the rat cell line IPC-81 to assess the cytotoxicity of a range of ILs. They screened 100 ILs, varying the headgroup, side-chain and anion of the ILs in order to observe the effect of each respective moiety on toxicity. Using the previously derived correlation between lipophilicity of the IL side-chain and cyctotoxicity using HPLC,[45] it was established that the side-chain was the most influential factor in

comparison with headgroup and anion in terms of toxicity. This supports the hypothesis about ILs and toxicity, that toxic effects are a direct result of lipophilic interactions with the cell membrane. Also observed was that the [NTf_2] anion had an intrinsic cytotoxic effect. However, when this anion was combined with a polar cationic moiety, the cytotoxitiy was not as severe. A significant result obtained from this study showed the presence of functional groups (ether, hydroxyl and nitrile) in the side chain of the ILs to lower cytotoxicity.

Epithelial cells are the sites for the first point of contact in an organism with toxic compounds. Three types of human epithelial cells have been examined in terms of cytotoxicity of ILs, namely, the breast cancer cell line MCF7, the carcinoma cell line HeLa and the Caco-2 cell line. Suggesting alternatives to imidazolium and pyridinium ILs, Salminen *et al.*[46] studied the toxicities of a range of hydrophobic pyrrolidinium and piperidinium ILs using the MCF7 cell line. The same increasing toxicity trend with increasing alkyl chain length was observed and the cytotoxicity of these compounds fell in the same range as imidazolium ILs. With few exceptions, the [NTf_2] anion was found to increase cytotoxicity in comparison with the bromide salt.

The cytotoxicity of ILs towards the HeLa cell line was investigated by Wang *et al.*[47] with imidazolium, pyridinium, triethylammonium and choline IL derivatives. Increasing toxicity with increasing side chain length was observed, and it was shown that changing the anion displayed a less significant effect than changing the side-chain length.

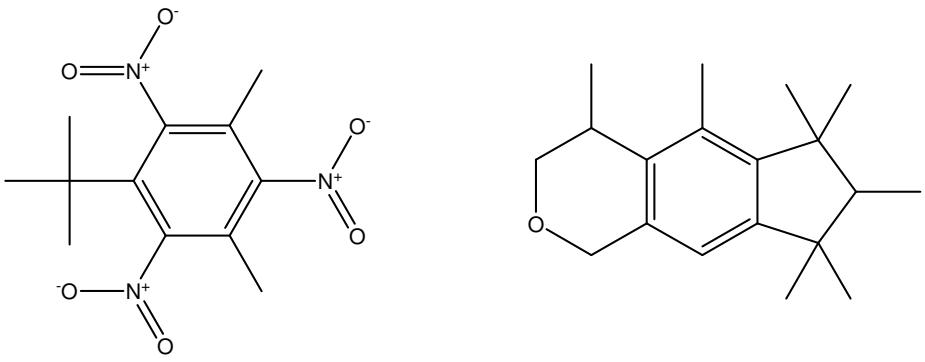
The cytotoxicity of imidazolium ILs towards the Caco-2 cell line was investigated by Garcia *et al.*.[48] Increasing alkyl chain length increasing the toxicity was observed and the ILs tested were shown to be more toxic than acetone, methanol, acetic acid and benzene.

1.2.2.6 Enzyme inhibition toxicity testing

The purified enzyme, acetylcholinesterase, from the electric eel (*Electrophorus electricus*) was used to test the affect of ILs on the inhibition of this enzyme.[49] The authors tested pyridinium, imidazolium and phosphonium ILs, with varying side-chain lengths, and also varying anions. Also investigated were the effects of inserting an aromatic substituent into the side chain. Regarding the cationic species of the ILs, results show pyridinium to have the highest inhibitory value, followed by imidazolium and finally phosphonium. The inhibitory effect of the ILs to increase with increasing alkyl chain length on the R_2 position of the cation was shown. Regarding aromatic

substituents in the side chain, they conclude that the slight increase in inhibition of the enzyme by the aromatic containing side chain ILs is due to the increased lipophilic nature in comparison with the straight chain moieties tested. The effect of lengthening the side chain at the R_1 position of the cation was investigated. No measurable difference in inhibitory values was observed, suggesting that the steric position of the lipophilic side chain also influences toxicity. The EC_{50} values for imidazolium and pyridinium ILs regarding the effect of the anion showed conflicting results. For imidazolium, [Br] and [Cl] showed the highest inhibitory effect, followed by [BF_4] and then [PF_6]. However, pyridinium showed the IL containing [PF_6] to be more inhibitory than that containing [BF_4].

Skladanowski *et al.*[50] used AMP deaminase isolated from rat skeletal muscle to investigate the toxicity of imidazolium based ILs. Together with the ILs tested were known pollutant musks, such as musk xylene (**39**) and galaxolide (**40**) (Figure 1.12).



Musk xylene
39

Galaxolide
40

Figure 1.12 Synthetic musks

IC_{50} values were used as a measure of toxicity of these compounds. Four [bmim] ILs were tested, each holding a different anion, namely, [BF_4] (**31**), [PF_6] (**27**), [Cl] (**30**) and [*p*Ts] (**41**). Unsurprisingly, all the tested ILs displayed IC_{50} values higher than those of the synthetic musks, thus indicating lower toxicity. The ILs were however indeed found to be toxic. The fluorine containing species of ILs [bmim][BF_4] (**31**) and [bmim][PF_6] (**27**) were found to be the most toxic (IC_{50}=5 μM), compared to the other two ILs tested (IC_{50}=10 μM).

1.2.2.7 Toxicity studies using higher organisms

The anatomically transparent free living soil roundworm, *Caenorhabditis elegans* (Figure 1.13) was studied regarding the toxic effects of imidazolium chloride ILs with chain lengths of C_4, C_8 and C_{14}.[51]

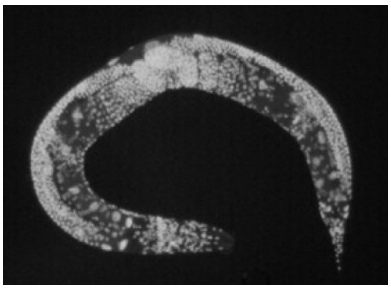


Figure 1.13 *Caenorhabditis elegans*[12]

It was found that the IL containing the longest alkyl chain was the most toxic, with toxicity decreasing thus from C_8 to C_4. The C_4 IL caused no adverse effects to the worms, while the C_{14} IL was lethal to them at all three concentrations of IL.

J. Randall *et al.* studied the effects of ILs containing imidazolium and pyridinium cations with varying chain length with anions [Br] and [PF_6], on the freshwater pulmonate snail, *Physa acuta*.[52] The acute toxicity, as well as the behavioural (locomotor and feeding) effects of the ILs on the snail were investigated. Results for the acute toxicity study show [ompyr][Br] (**26**) to be the most toxic IL investigated, with [TBA][Br] (**42**) being the least toxic. LC_{50} values in general then decreased with increasing alkyl chain length. The range of LC_{50} values obtained for the ILs studied are shown to be in the same range as values for organic solvents such as ammonia and phenol. The imidazolium and pyridinium containing cations could not be distinguished according to toxicity level, as [hmim][Br] (**23**) was shown to be more toxic than [hmpyr][Br] (**24**), while [omim][Br] (**25**) was less toxic than [ompyr][Br] (**26**). The grazing rate of the snails decreased with increasing concentration of IL and also upon increasing chain length. The results for the movement study showed the movement of the snails to decrease initially with low concentrations of ILs, but then increase above a certain threshold where IL concentration increased. The combination of the results for locomotor and feeding behaviour shows an escape response, implying that the organisms search for refuge from the IL when a certain concentration threshold is reached.

The toxicity of ILs to zebrafish (*Danio rerio*) (Figure 1.14) was investigated.[53]

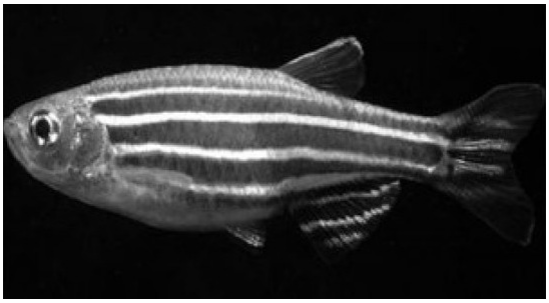


Figure 1.14 Zebrafish (*Danio rerio*) [12]

Ammonium, imidazolium, pyridinium and pyrrolidinium based ILs were used. The ammonium based ILs were shown to be by far the most toxic, with LC_{50} values lower than those of commonly used organic solvents, i.e. MeOH, DCM, ACN and TEA. The fish exposed to these ILs showed erratic behaviour compared to the control fish, and also upon histopathological inspection, numerous abnormalities were noted in the fish. All other ILs exhibited LC_{50} values greater than 100 mg/L, therefore were not investigated further, and deemed by the authors to be 'non-highly lethal towards zebra fish'.

Although these tests give some indication of the relationship between structure and toxicity, more in-depth studies are needed to confirm this preliminary data. Relating to structure, similar trends occur in various test systems, therefore this aids the advancement of future SAR studies.

Some ILs studied have been clearly shown to be toxic, although their risk to the environment may not be as severe if they do not persist in the environment and are readily degraded.

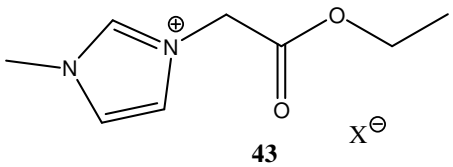
1.2.3 History of Biodegradability of ILs

ILs adding to anthropogenic waste is a factor hindering their valid classification as 'green solvents'. The fate of organic chemicals in the environment is dependent on the action of living organisms to breakdown the compound into its natural components, returning it to the cycle of life. Degradation can be carried out by higher organisms, by utilising a family of isozymes called cytochrome P_{450}. Cytochrome P_{450} are the key enzymes in the MFO (mixed function oxidase) system. This detoxification system is probably the most important element of phase I metabolism.[54] The enzymes facilitate the oxidation of aliphatic groups in the compounds to be degraded. Microbial transformation is however the most important process that can decompose an organic xenobiotic chemical in the environment.[54] The main biodegradation pathways include

hydrolysis and oxidation. Hydrolysable functionalities, such as esters, amides and urethanes, increase biodegradation potential. Flexibility of the main alkyl chain of a compound also aids biodegradation as it facilitates the binding of the molecule to the active sites of the enzymes.

Biodegradation testing is carried out to determine the fate of chemicals in the natural environment. Due to the great variety of biodegradation mechanisms in the natural environment, many methods are used to test biodegradation of substances. The methods that have been thus far used to test the biodegradation of ILs are the Sturm and the Closed bottle test, approved by The Organisation for Economic Cooperation and Development (OECD 301B and D respectively), and also the BOD_5 test.

Due to the similarity between ammonium and imidazolium based surfactants and some common ILs, Gathergood *et al.* studied the factors applied to surfactants to improve their biodegradation.[55] They found that reduced branching in LASs (linear alkyl sulfonates)[56] and the presence of a possible site for enzymatic hydrolysis in QACs (quaternary ammonium compounds)[57-60] led to improved biodegradation. Using this knowledge together with following Boethlings rationale of identifying three factors that are important in the design of biodegradable compounds,[59] Gathergood *et al.* synthesized imidazolium based ILs with ester and amide functionalities in the side chain. These functionalities were chosen above alcohol or carboxylic acid functionalities due to their reduced reactivity in comparison, while still incorporating possible sites of enzymatic hydrolysis into the side chain. Together with investigating their biodegradability using a modified Sturm test (OECD 301B) and closed Bottle Test (OECD 301D), and comparison to the popular [bmim] series, they investigated the melting point of the prepared compounds, in an effort to design biodegradable ILs without compromising the depressed melting points that make these solvents so attractive. All ILs prepared had a melting point below 100 ºC, with almost all ILs containing the ester functionalities being liquids at RT, however ILs containing the amide functionality were more likely to be solids. Preliminary studies on biodegradability involved testing the amount of CO_2 evolved from wastewater micro organisms in an aerobic aqueous medium containing the compound to be tested, using the Sturm test. A CO_2 evolution level of above 60 % was considered to pass this test. Bromide (**43a**) and [BF_4] (**43b**) ILs (Figure 1.15) and [bmim][PF_6] all showed values of CO_2 evolution close to or equal to 60 %.



43

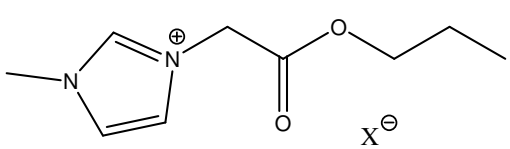
X: Br (**a**) or BF_4 (**b**)

Figure 1.15 Bromide and [BF_4] imidazolium IL (**43a** and **b**) containing ester functionality

Using OECD 301D, to an aerobic aqueous medium inoculated with wastewater micro organisms, IL is added, and the depletion of dissolved molecular oxygen is measured. 60 % is again the pass rate for this test, with compounds obtaining above this value being deemed readily biodegradable. The results obtained using both these tests differed. Although the ILs with the ester functionality increased biodegradation compared to [bmim][BF_4] (**31**) and [bmim][PF_6] (**27**), bromide salt esters with alkyl chain length ≥ 4 being the most biodegradable, the biodegradability level obtained was significantly lower than that obtained using the Strum test.

The lag phase period of the organisms' life cycle is reduced using a denser inoculum of organisms, therefore the amount of compound degraded in a certain time frame increases. The authors suggest that the difference in results obtained may be attributed to the fact that the inoculum density using the closed bottle test is lower than that used in the Sturm test.

Advancing from their preliminary biodegradability studies, this group began investigating ILs containing an ester group in the side chain with regard to the effect the anion had on biodegradation.[21] Biodegradation was again tested using the closed bottle test (OECD 301D). They tested the [bmim] and [3-methyl-1-(propoxycarbonylmethyl) imidazole] (**44**) ILs with different counterions, [Br], [BF_4], [PF_6], [NTf_2], [$N(CN)_2$], and [$OctOSO_3$] (Figure 1.16).



44

X = Br:**a**
BF_4 :**b**
PF_6: **c**
NTf_2: **d**
$N(CN)_2$: **e**
$OctOSO_3$: **f**

Figure 1.16 [3-methyl-1-(propoxycarbonylmethyl) imidazole] cation with differing anions

The ILs containing the ester functionality showed the highest biodegradation in comparison with the [bmim] ILs, with the ester linkage containing IL and the

[$OctOSO_3$] anion (**44f**) being the most biodegradable. No significant change however was noted between the varying anions.

BOD_5 measurements were carried out by Wells and Coombe[27] on imidazolium, pyridinium, phosphonium and ammonium ILs (**27, 30** and **45**, **46** and **48**) to establish their biodegradation (Figure 1.17). They also examined anion effects by measuring the biodegradation of simple compounds of the appropriate anion, for example **47**. Three concentrations were tested. The percentage uptake of oxygen after 28 days, and the complete organic carbon removal from the system were investigated. Most of the ILs studied, due to their high toxicity were resistant to biodegradation. 6 ILs were inhibitory at the test concentration.

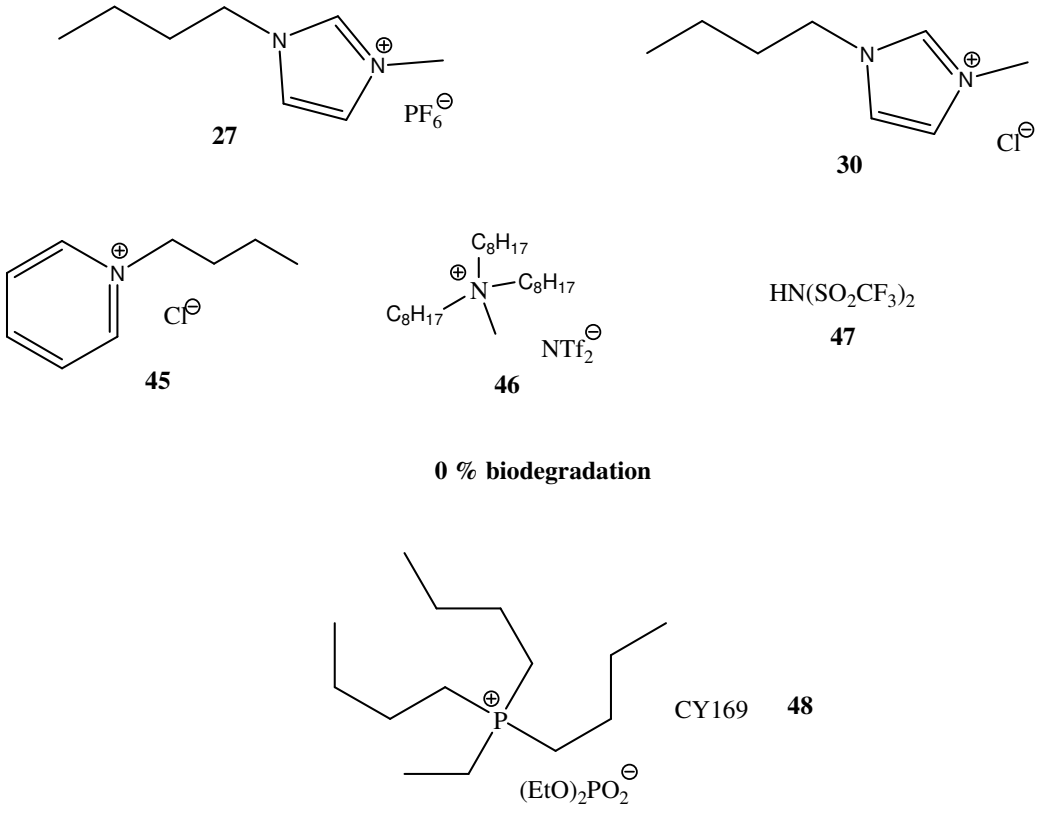


Figure 1.17 Biodegradation of selected ILs

Romero *et al.*[20] found a range of imidazolium ILs not to be biodegradable by measuring BOD_5 of aqueous samples of the ILs.

Docherty *et al.*[61] used an OECD DOC (dissolved organic carbon) Die-Away test to examine the biodegradability of imidazolium and pyridinium ILs by an activated sludge microbial community. While none of the imidazolium ILs could be classed as biodegradable, because after 28 days only partial mineralization was observed, the

pyridinium ILs of hexyl and octyl side chains were fully mineralized. Neither of the butyl side chain ILs for the imidazolium and pyridinium derivatives were biodegradable.

Stolte *et al.*[23] also used an activated sludge microbial community to investigate the biodegradation of imidazolium and pyridinium ILs. The long alkyl length side chain was found to be more readily degraded than the shorter side chains. Considering the shorter side chains, no improvement was observed even with the introduction of functional groups such as ether or nitrile. Harjani *et al.*[62] use the CO_2 Headspace test (ISO 14593) to evaluate the biodegradability of a range of pyridinium ILs (**49** - **51**) (Figure 1.18).

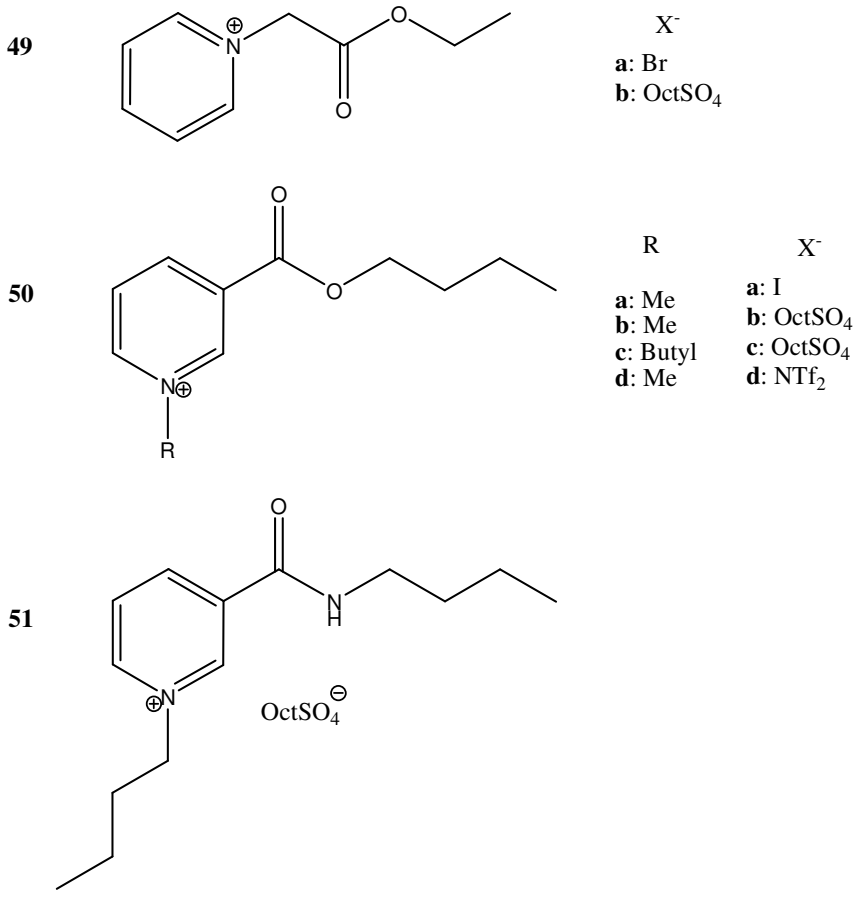


Figure 1.18 Pyridinium ILs

It was found that these ILs constituting the pyridinium cation were indeed biodegradable. Interestingly, the use of the [$OctOSO_3$] anion as opposed to the bromide anion did not significantly increase the biodegradation, an increase in only 2 % being observed from **49a** to **49b** (87 to 89 % respectively). An increase in alkyl chain length of the side chain was observed to increase biodegradation; **50b** displayed a

biodegradation value of 75 %, while the butyl derivative of this compound showed an increased value of 82 %. The introduction of an amide functionality for the case of the nicotinamide IL (**51**) drastically decreased the biodegradation to 30 %.

1.3 Synthesis of CILs based on the lactate or mandelate moiety

1.3.1 Introduction

Although the first evidence of chiral solvents used in asymmetric synthesis dates back to 1975, when Seebach and Oei[63] used a chiral aminoether as a solvent for the electrochemical reduction of ketones, little has been seen since due to the difficult synthesis of chiral solvents and their high cost. In the past few years however, it is evident that the field of chiral ILs (CIL) has been steadily coming into effect.[64-68] It can be noted that preliminary work in this field concentrated on the preparation of the CILs, with later work progressing to the application of these prepared CILs.

According to a search done using SciFi Scholar and the term 'chiral ILs', results show that since the initial tentative introduction to CILs in the early years of the 21st century, the amount of work published in the last three years is steadily increasing (Figure 4).

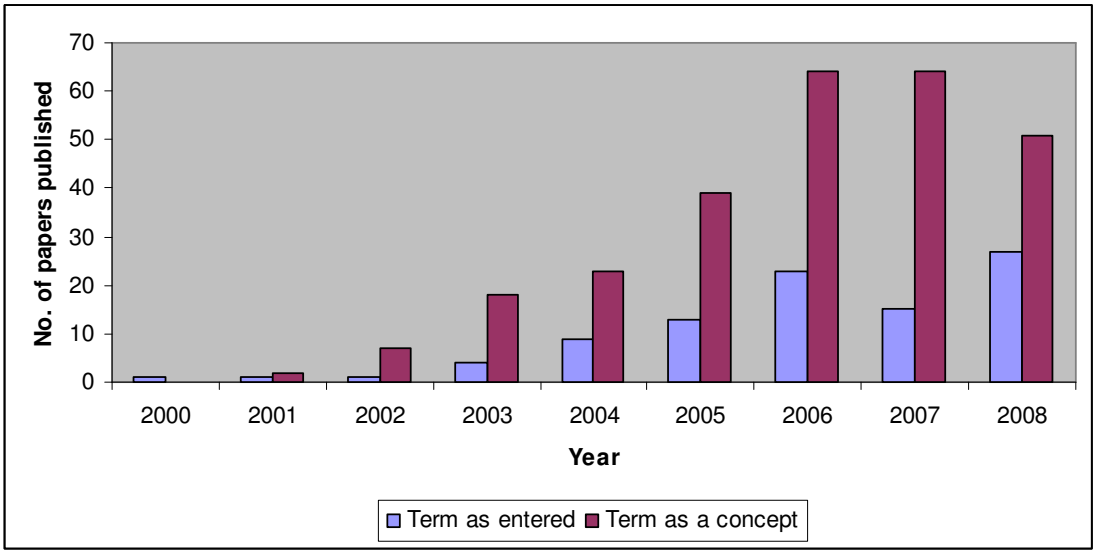


Figure 1.19 SciFi Scholar search results with term 'chiral ILs'

For the full potential of ILs to be reached they should be widely used on an industrial basis as alternatives to VOC's. One of the principal reasons hindering their manufacture and use on a large scale is the high cost of starting materials. Lactic acid (**52a/b/c**) and mandelic acid (**53a/b/c**) serve as useful and cost-effective compounds for chirality introduction to the IL.

1.3.2 Lactate-based CILs

1.3.2.1 Lactate moiety in CIL anion

Along with achiral ILs, in 1998, Seddon *et al.*[69] used 1-butyl-3-methylimidazolium lactate (**54**) as an alternative to lithium perchlorate-diethylether mixtures in Diels-Alder reactions. The synthesis of the chiral lactate IL was performed by reaction of sodium (*S*)-2-hydroxypropionate (**55**) and [bmim][Cl] (**30**) in acetone (Figure 1.20). It was found that although the lactate IL showed to be as effective as the other ILs used for the reaction of cyclopentadiene and 3 different dienophiles (in this case, ethylacrylate and cyclopentadiene), no enantioselectivity was observed.

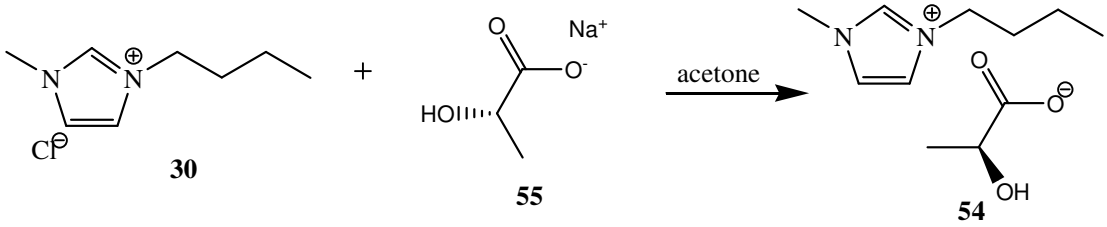


Figure 1.20 Synthesis of chiral lactate IL

To date, this is one of the few examples where the chirality of the IL resides in the anion.

Xin *et al.*[70] used their cyclic guanidinium lactate IL (**56**) as a solvent and the catalyst for a Knoevenagel condensation of aromatic aldehydes with active methylene compounds (Figure 1.22). The synthesis of the IL proceeded by neutralisation of the guanidinium moiety (**57**) with lactic acid (**52**) in 90 % yield in one step (Figure 1.21).

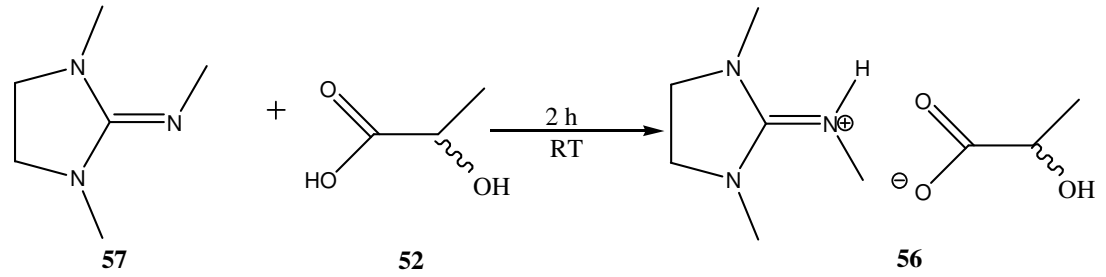


Figure 1.21 Synthesis of guanidinium lactate IL

With few exceptions, good yields were obtained with a range of substrates (**58**/**59**) (> 92 %) in short time periods (< 7 minutes).

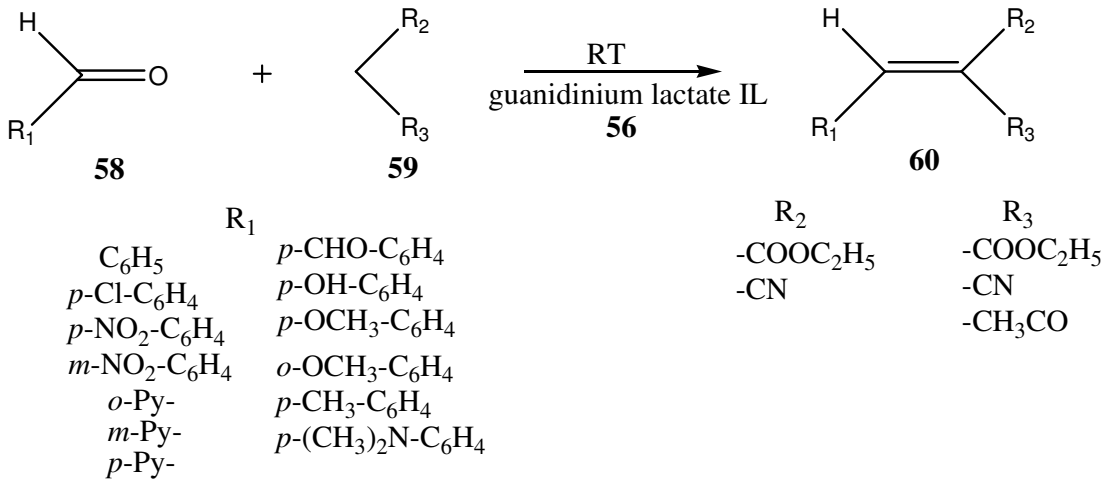


Figure 1.22 Knoevenagel condensation

Recylcing of this IL proved efficient; after 6 runs the percentage yield of a model reaction had only decreased by 0.4 % (from 96.8 to 96.4 %).

Neutralization of a guanidinium moiety with lactic acid (**52**) was again performed by Zhu *et al.*[71] to furnish 1,1,3,3-tetramethylguanidine lactate IL (**62**) (Figure 1.23).

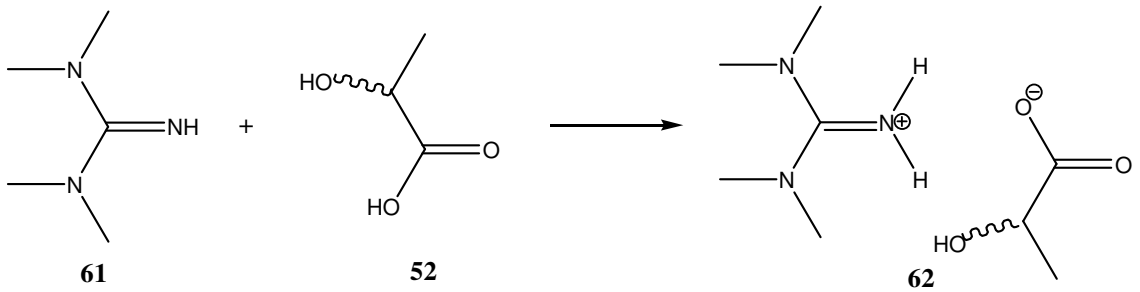
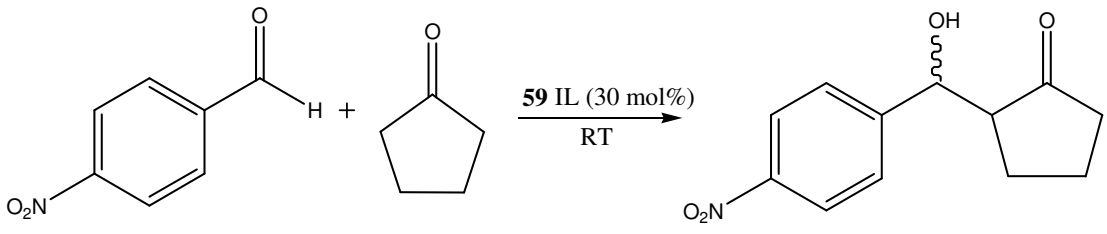


Figure 1.23 Synthesis of 1,1,3,3-tetramethylguanidine lactate (**62**)

This IL (**62**) was successfully used as a recyclable catalyst and solvent medium for direct aldol reactions. Respectable yields and diastereoselectivities were obtained using a range of aldehydes and ketones. A model reaction of 4-nitroaldehyde with cyclopentanone was recycled 3 times, with little decrease in percentage yield, and relatively small change in diastereoselectivity (Figure 1.24).



63 **64** **65**

Run	Yield (%)	*syn/anti*
1	97	68/32
2	97	70/30
3	95	64/36
4	93	68/32

Figure 1.24 Aldol reaction

The same tetramethylguanidinium lactate IL (**62**) was used by Liang *et al.*[72] for efficient Michael addition reactions. As previously described the IL acted as dual catalyst and solvent for the reactions of chalcones, nitromethanes and active methylene compounds. The reaction between diethyl malonate and chalcone was recycled 5 times with the percentage yield decreasing only 1 % by the final run (from 99 % to 98 %).

1.3.2.2 Lactate moiety in CIL cation

In 2004, Jodry *et al.*[73] prepared imidazolium CILs (Figure 1.25, CILs **66a** – **e**) from (*S*)-ethyl lactate (**52b**) (Figure 1.25). This is the only example of a lactate IL with the lactate moiety residing in the cation of the IL. All salts were shown to be liquids at RT, with the exception of the triflate anion containing CIL, however, racemization of the chiral salts was shown to easily occur in a basic environment.

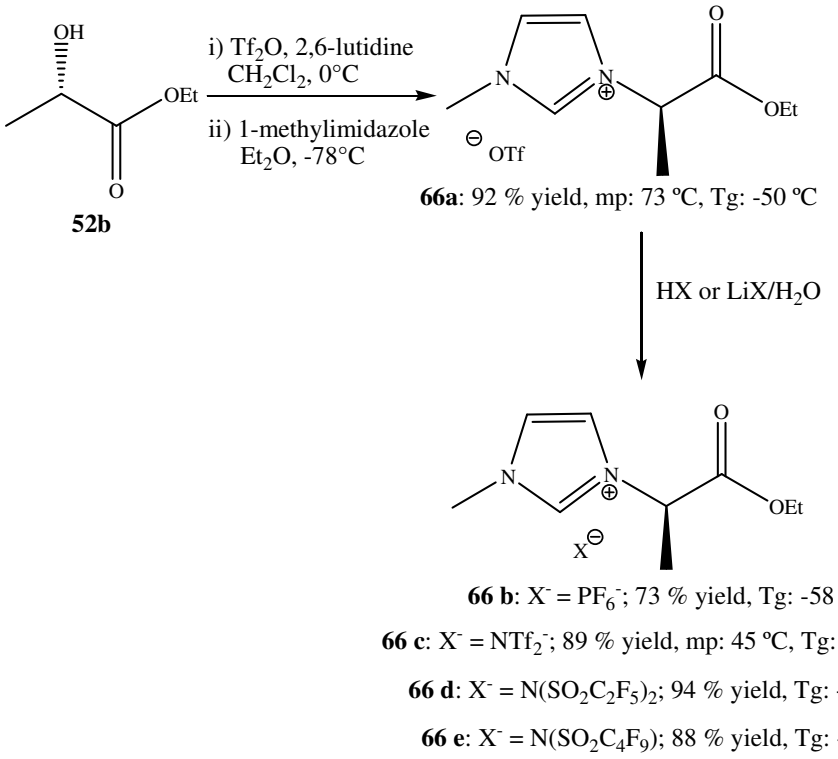


Figure 1.25 Synthesis of chiral imidazolium ILs

The enantiomeric purity of the CILs was investigated by ^{1}H NMR studies. The racemic triflate salt was first measured by using Lacour's TRISPHAT anion as NMR chiral shift reagent. When this salt was added to the racemic CIL a separation of signals of 2 enantiomers could be seen on the ^{1}H NMR spectrum. However, when the (*S*) enantiomers of the triflate salt is used, only one set of signals could be observed, thus confirming enantiomeric purity of the product.

1.3.2.3 Lactate moiety used in synthesis of CIL

Wang *et al.*[74] synthesised imidazolium CILs derived from the chiral pool, and also investigated their usefulness as chiral induction solvents. The enantioselective Michael addition of diethyl malonate (**67**) to 1, 3-diphenyl-prop-2-en-1-one (**68**) (Figure 1.26) was investigated.

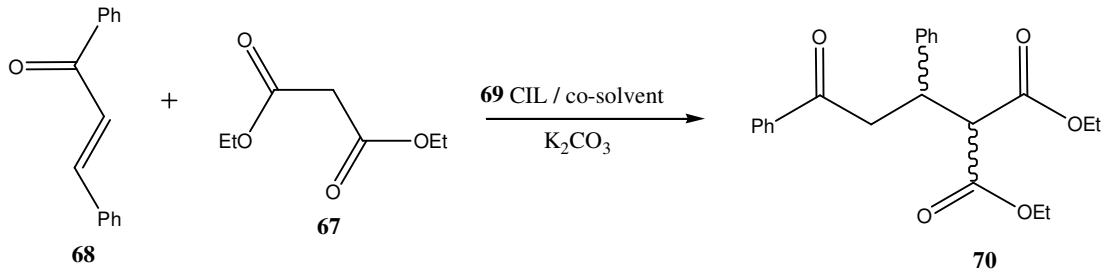


Figure 1.26 Enantioselective addition of diethyl malonate to 1,3-diphenyl-prop-2-en-1-one

The tartrate derived CIL (**69**) was synthesised in 5 steps (Figure 1.27) in 51 % overall yield, however the melting point of the resulting bromide salt was high (182 – 183 °C).

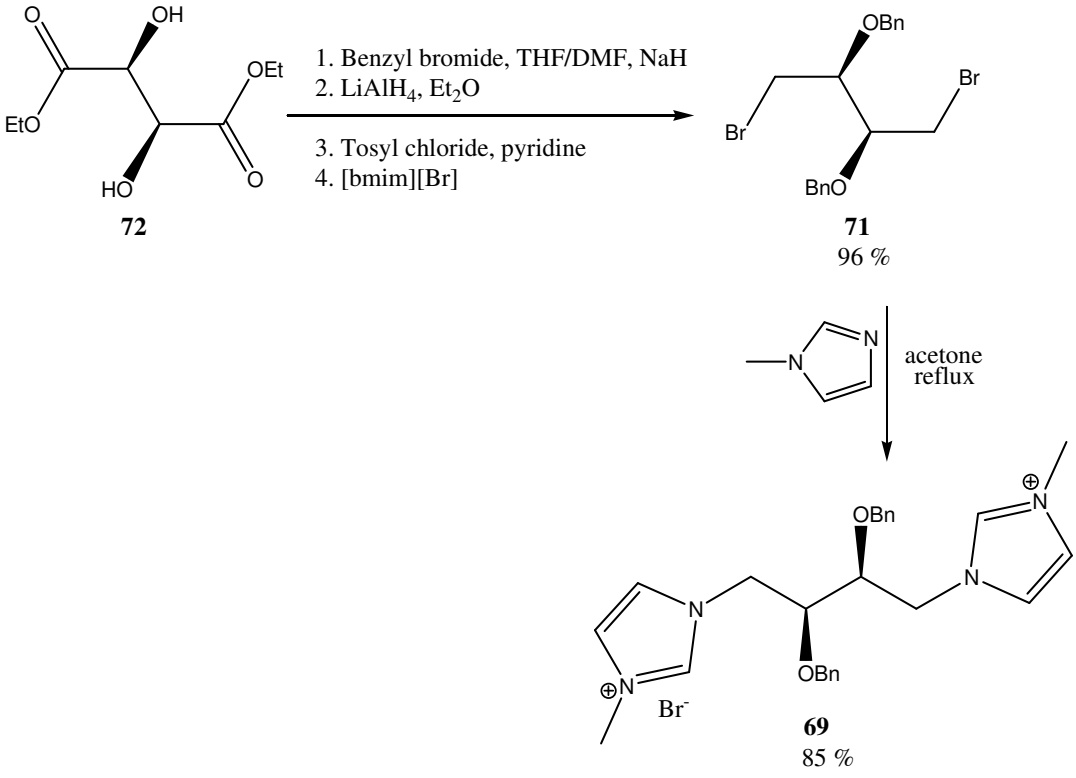


Figure 1.27 Synthesis of CIL derived from tartrate

In an effort to reduce the melting point, unsymmetrical L-(–) ethyl lactate (**73**) was used as starting material for the 5 step synthesis of the corresponding salt **74** (Figure 1.28) in 60 % overall yield, thus reducing the melting point to 57 – 58 °C.

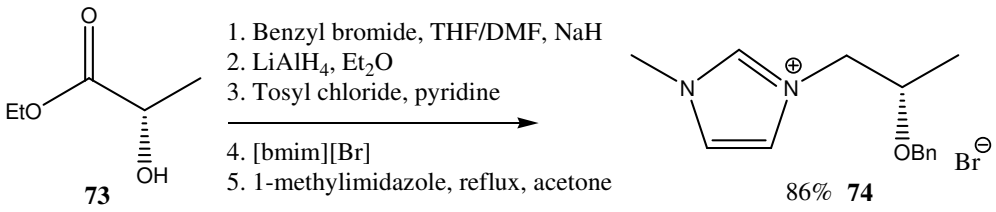


Figure 1.28 Synthesis of CIL from L-(-)ethyl lactate

Anion exchange reactions with [BF_4] and [PF_6] salts (Figure 1.29) resulted in various CILs (**75**-**78)** in good yields (87 – 92 %), the lactate-based [BF_4] salt (**75**) giving the lowest melting point salt (41 – 42 °C).

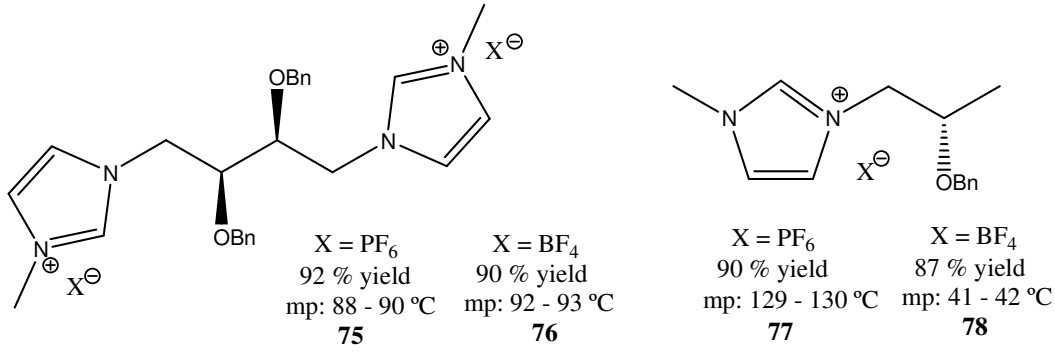


Figure 1.29 Anion exchange reactions

As the melting points of the CILs were relatively high, a co-solvent was used in addition with CIL **78** for the Michael addition reactions, the best result being obtained with toluene as co-solvent (96 % yield, 25 % ee).

In order to investigate the use of CILs in the ATRP of acrylates, Biedron *et al.*[75] synthesised an imidazolium CIL (**79**) in good yield (71 %) in 2 steps followed by anion exchange (Figure 1.30).

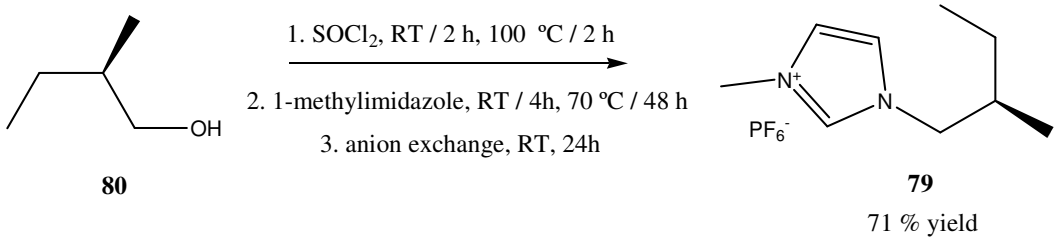


Figure 1.30 Synthesis of imidazolium CILs from chiral alcohol

The investigation showed the CIL to have a negligible effect on polymer tacticity. Their investigation was however limited by the expensive starting material used to synthesise their CIL. In a bid to overcome this problem, they synthesised 2 CILs (**81a** and **b**) from the more cost efficient lactic acid (Figure 1.31).

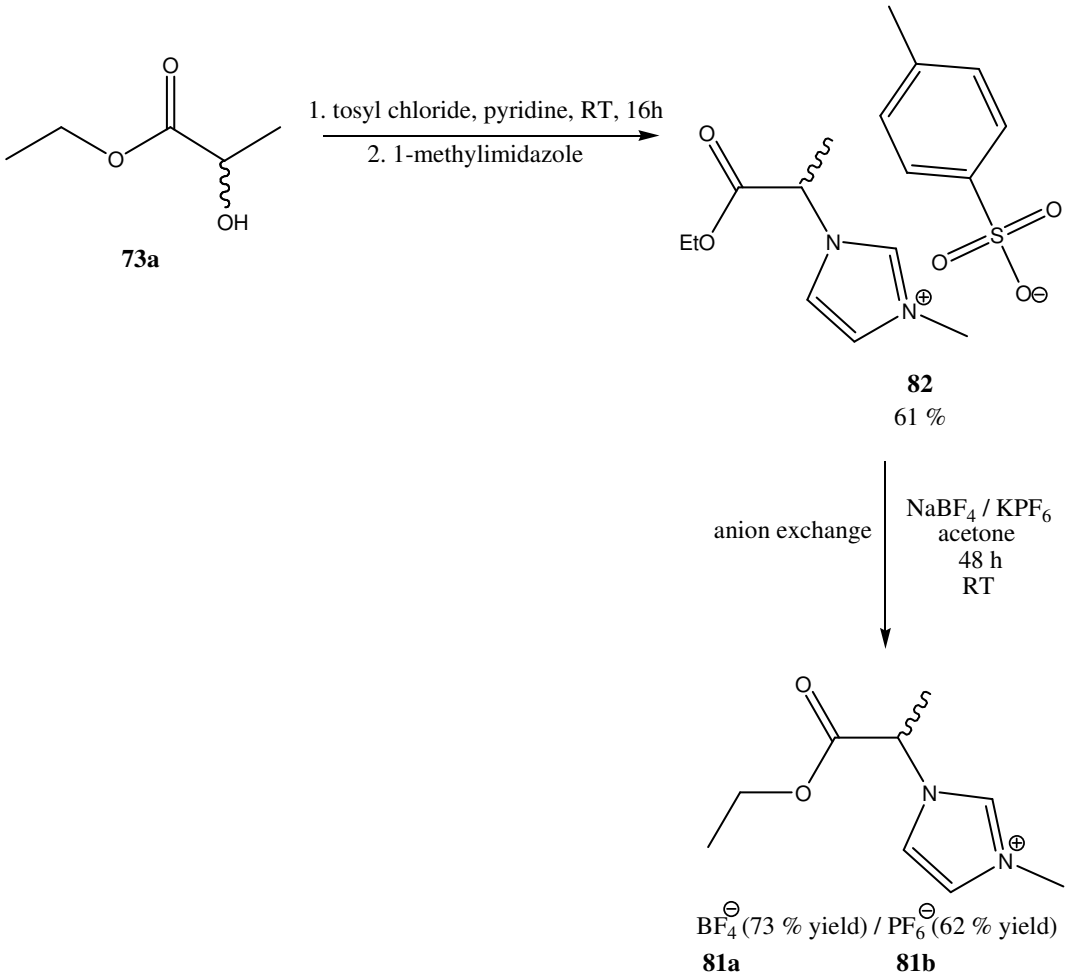
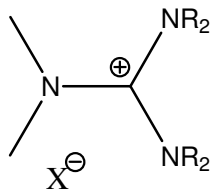


Figure 1.31 Synthesis of imidazolium based CILs from lactic acid

Their continuing investigation with their newest CILs showed again that the CIL did have an effect on polymer tacticity.

1.3.3 Mandelate-based CILs

The chiral mandelate moiety is only presented so far in the anion of the CIL. Together with synthesising a lactate derivative, Branco *et al.*[76] synthesised a mandelate guanidinium CIL (**83a**). Their guanidinium ILs were obtained by simple anion exchange of the chloride salt with the readily available chiral anion in DCM at RT (Figure 1.32).

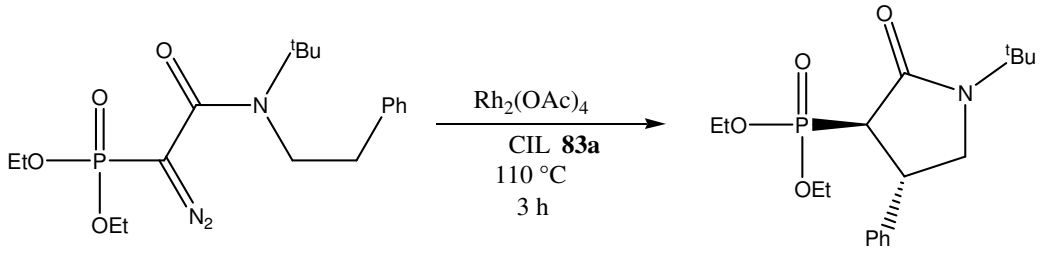


R = *n*-hexyl
X = mandelate/lactate
a **b**

83

Figure 1.32 Guanidinium ILs

They synthesised their novel CILs using readily available anions as the chiral source. They subsequently used these CILs as media for two procedures, namely a Rh(II) carbenoid asymmetric C-H insertion and a Sharpless asymmetric dihydroxylation, as the source of chiral induction. The lactate CIL displayed the lowest viscosity for the range of their ILs. The T_g values for the mandelate and lactate guanidinium ILs were -56.9 and 72.9 °C respectively. Using the mandelate derivative (**83a**) as reaction solvent and chiral induction source, they obtained enantioselectivity of 27 % for the asymmetric C-H insertion (Figure 1.33).



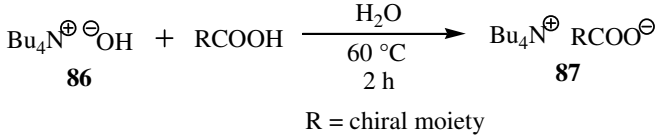
84 **85**

72 % (*trans/cis* = 67:33)
ee = 27 %

Figure 1.33 Asymmetric C-H insertion

However, a more impressive enantioselectivity was obtained, up to 85 % ee, using their quinic guanidinium CIL for Sharpless asymmetric dihydroxylation.

By reaction of tetrabutylammonium hydroxide (**86**) with a range of amino acids and other organic acids including mandelic acid, Allen *et al.*[77] prepared a range of CILs (**87**) (Figure 1.34). The novel CILs were synthesised by reaction of the chiral acid with tetrabutylammonium hydroxide.



86 **87**

R = chiral moiety

Figure 1.34 CILs prepared from [TBA][OH]

Both L and D mandelate derivatives of the CILs were colourless liquids at RT and no decomposition was observed when heated at 110 °C for 24 h.

1.4 Hydrogenation in ILs

1.4.1 Introduction

One of the principal present-day dilemmas facing the field of transition metal catalysis is the inefficient recycling and reuse of costly catalysts and ligands. The use of ILs is rapidly advancing in this discipline. Due to their physico-chemical properties, compared with those of organic and aqueous media, ILs provide a means of catalyst immobilization. The non-nucleophilic nature bestows an inert reaction medium that can provide an extension of the catalyst lifetime. Recyclability of the catalyst system is a key attribute of IL media and it is this extension of catalyst performance that is a main factor attracting research in this field. Low-polarity compounds, for example diethyl ether and *n*-hexane, are commonly insoluble in ILs. This varying solubility of the aforementioned organic solvents in ILs provides a suitable environment for biphasic catalysis. The positive aspects of homogeneous and heterogeneous catalysis are combined using a biphasic system. In this phase system, the catalyst resides in the IL and the substrates/products reside in the alternate phase. This system can implement a cost-effective way to successfully separate the desired product by simple decantation, leaving the catalyst immobilised in the IL, equipped for reuse. In the case of monophase catalysis in ILs, where the substrates are soluble in the IL medium, simple extraction or indeed facile distillation, due to the low vapour pressure of the IL, can be utilised as an alternative method for separating products from the IL/catalyst system. The reduced polarity of the hydrogenated products in comparison with the substrates can also be exploited for separation from the IL/catalyst phase. The increasing difference in polarity between the IL and hydrogenated product can render the product insoluble in the IL thus allowing for mere decantation of the product from the IL leaving the IL/catalyst phase intact.

Catalytic hydrogenations in ILs began in 1995 with the almost simultaneous work of Chauvin[78] and Dupont.[79]

1.4.2 Achiral transition metal hydrogenation in ILs

Commonly used heterogeneous catalysts such as palladium or platinum on solid supports are among the catalysts employed for the hydrogenation of achiral substrates in ILs. Although increased temperature and pressure may be a necessity using the IL, classic palladium and platinum catalysts have been shown to give superior results when used in an IL as opposed to a common organic solvent.

Xu *et al.*[80] used a range of imidazolium ILs containing [BF_4] and [PF_6] anions for the catalytic heterogeneous hydrogenation of halonitrobenzenes (**88**) to the corresponding haloanilines (**89**) (Figure 1.35).

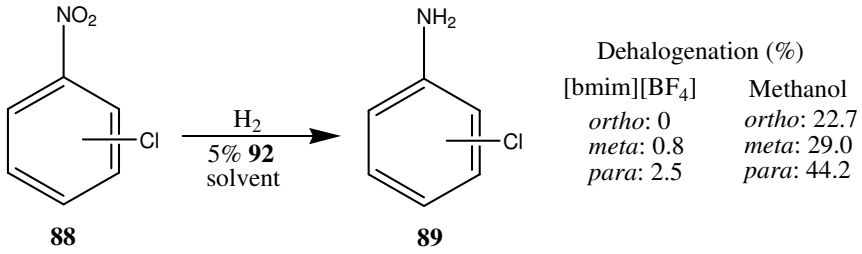


Figure 1.35 Hydrogenation of halonitrobenzenes to haloanilines

Raney nickel (**90**), platinum on carbon (**91**) and palladium on carbon (**92**) were employed as metal catalysts, and methanol was used as a reference organic solvent as it has similar polarity to [bmim][BF_4] (**31**) and is the most widely used in heterogeneous catalysis hydrogenations. Although increased temperatures and pressures were required for the IL systems, they performed better as reaction solvents for these reactions, the dehalogenation being greatest for all substrates tested in methanol over ILs. Taking for example *ortho*, *meta* and *para* chloronitrobenzene, and 5% Palladium on Carbon (**92**), for which the greatest differences in results between IL and organic solvent were evident. Using [bmim][BF_4] (**31**), dehalogenation ranged from as low as 0 % with *o*-chlronitrobenzene to 0.8 % with the *meta* derivative and 2.5 % with the *para* substituted derivative. However when methanol was used as solvent, dehalogenation ranges from 22.7 % and 29.0 % (*ortho* and *meta* chloronitrobenzene respectively) to as high as 44.2 % for *para*-chloronitrobenzene. The same trend was evident using catalysts 5% **90** and **91**, however albeit to a lesser extent.

Anderson *et al.*[81] chose the α,β-unsaturated aldehydes, citral (**93**) and cinnamaldehyde (**94**) (Figure 1.36 and Figure 1.37), to demonstrate the superior selectivity obtained using pyridinium, imidazolium and ammonium ILs for hydrogenation reactions over

common organic solvents. A classic palladium supported on carbon catalyst (**92**) was used for the reactions.

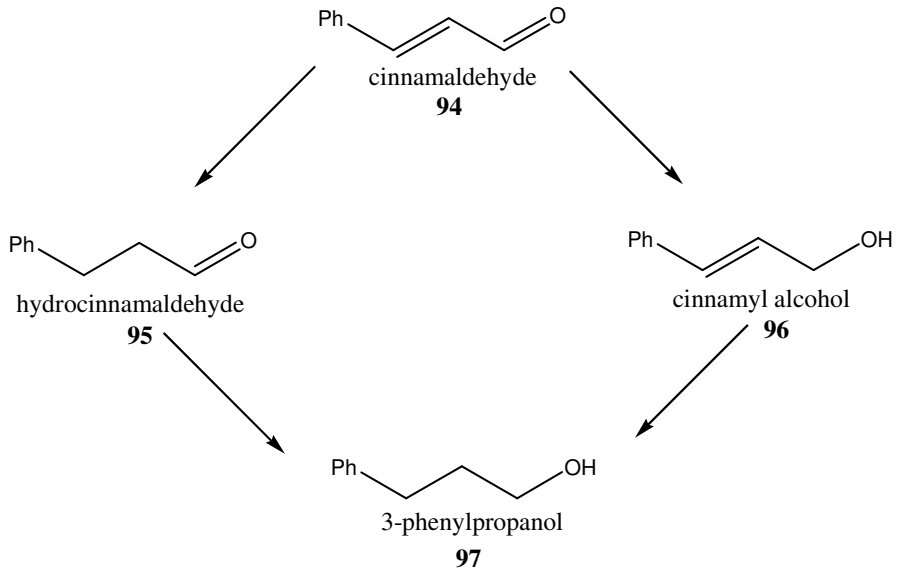


Figure 1.36 Reaction pathway of cinnamaldehyde hydrogenation

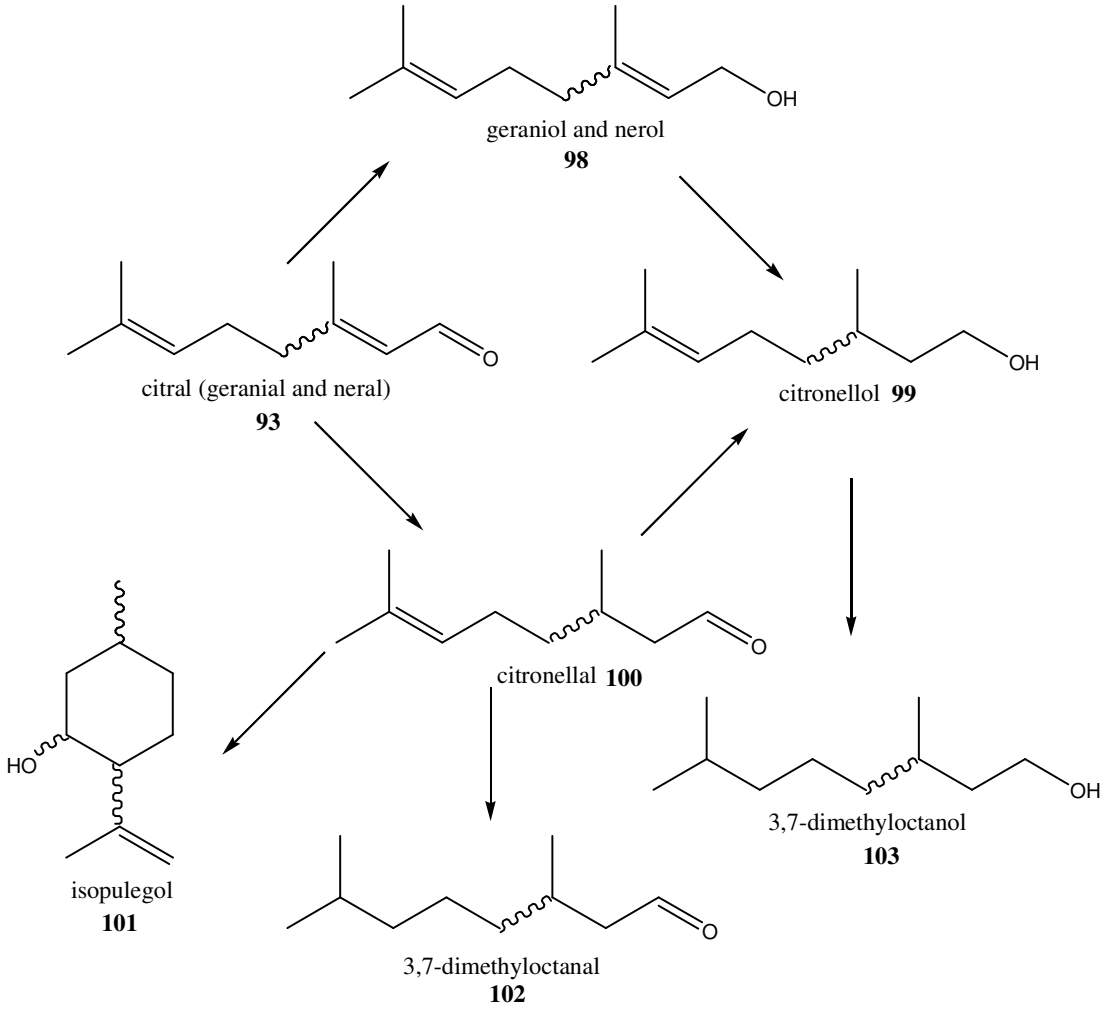
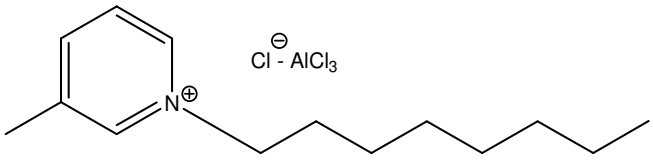


Figure 1.37 Reaction pathway of citral hydrogenation

In the case of cinnamaldehyde (**94**), although the temperature was increased for the reaction carried out in the IL (60 ºC), the selectivity to hydrocinnamaldehyde (**95**) obtained using the IL (78-100 %) was far superior to that obtained using the selected organic solvents, which did not surpass 89 % (78-89 %). Worth noting for these hydrogenations is the varying of selectivities across a series of [bmim] ILs. [Bmim][PF_6] (**27**) showed selectivities of 100 %, [bmim][OTf] (**105**) 91 %, and 78 % for [bmim][OAc] (**105**). Recycling of the [bmim][BF_4] system showed catalyst activity to decrease by 50 % upon the first recycle but remained constant for five successive reactions. The selectivity however remained almost constant for all recycles carried out. The authors do note that if the IL system is treated for one hour prior to reaction commencement with hydrogen gas, in the absence of substrate, the recycling ability of the system can be improved. In the case of citral hydrogenation, similar trends were

observed. The selectivity towards citronellal (**100**) obtained using various IL ranged from 81-100 %, with the organic solvents displaying only 62-77 % selectivity.

Geldbach *et al.*[82] attemped to generate catalysts from metal chlorides in the Lewis acidic IL, [*N*-Octyl-3-picolinium]Cl-$AlCl_3$ (**106**) (Figure 1.38), by dissolving a series of metal chlorides in the IL and adding the substrate benzene.



106

Figure 1.38 [*N*-Octyl-3-picolinium]Cl-$AlCl_3$ (**106**)

Hydrogen was then added to the biphasic mixture and the percentage conversions to cyclohexane recorded. Of all the metal chlorides used, only the palladium ($PdCl_2$) and platinum (K_2PtCl_4) examples showed any significant activity, with 57 and 99 % conversion respectively. The platinum containing metal chloride was investigated further in relation to catalyst concentration and temperature as it showed the most promising result. Generally, higher catalyst loadings gave increased conversion, and raising the temperature also led to an increase in conversion. This groups research also extends to the examination of a ruthenium cluster catalyst in [bmim][BF_4] (**31**) for the same hydrogenation reactions however no activity was observed using the IL.

Although ILs have many 'green' attributes when it comes to their use in hydrogenation reactions, in some cases, the common organic solvent prevails. Using the bimetallic catalyst system, Ag-In/SiO_2 for the hydrogenation of the α,β-unsaturated aldehyde citral (**93**) to selectively form acyclic/allylic terpene alcohols geraniol (**98a**) and nerol (**98b**), Steffan *et al.*[83] showed the non-polar solvent hexane to be superior to the polar [bmim][NTf_2] (**107**) IL. The chemoselective hydrogenation of citral (**93**) to geraniol (**98a**) and nerol (**98b**) was lower in the IL compared to the organic solvent. Their results depict lower conversion of citral in ILs compared to hexane and suggest the lower solubility of hydrogen in the IL to be the limiting factor.

While investigating the mass transfer effects in the hydrogenation of phenyl acetylene (**108**) to styrene (**109**) and ethyl benzene (**110**) (Figure 1.39), using their rotating disc reactor, Hardacre *et al.*[84] found an IL to give lower reaction rates than a molecular solvent.

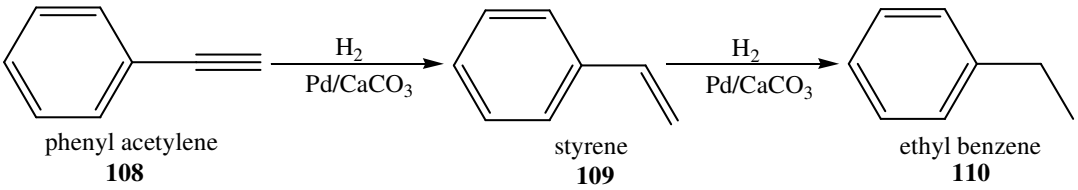


Figure 1.39 Hydrogenation of phenyl acetylene

Using palladium on calcium carbonate as catalyst, they investigated varying properties between [bmim][NTf_2] (**107**) and heptane, for example the effect of phenyl acetylene concentration in the solvent and the rotation speed. The rate of reaction was reduced in the IL compared to the organic solvent, postulated by the group to be due to the varying rate of diffusion of gaseous hydrogen through the liquid medium to reach the catalyst surface.

Recently Khodadadi-Moghaddam *et al.*[85] investigated the kinetic parameters of the hydrogenation of a non-polar substrate, cyclohexene (**111**), in mixtures of the IL 2-hydroxyethylammonium formate (**112**) and various alcohols (methanol, ethanol and propan-2-ol). Using a platinum on aluminium oxide catalyst, the rate constant for the reaction carried out in the IL/propan-2-ol mixture was twenty eight times higher than when carried out in the alcohol as sole reaction medium. From studying the solvent effects on the reaction, the authors explain this result to be due to the varying polarities of solvent and substrate: they suggest that due to the polar nature of the IL, the non-polar cyclohexene (**111**) is more abundant on the catalyst surface, therefore promoting the reaction.

Biphasic reaction conditions are one important method for hydrogenations using homogeneous catalysts when efficient recycling of catalyst is of importance. Hydrogenation reactions have been carried out using rhodium and ruthenium catalysts in biphasic systems using imidazolium and ammonium-based ILs. With the use of a rhodium catalyst ([$Rh(\eta^4\text{-}C_7H_8)(PPh_3)$][$BF_4$]) (**113**), Dyson *et al.*[86] demonstrated a biphasic hydrogenation of an alkyne (**114**) using IL and water phases. Their system consisted of [omim][BF_4] (**37**) containing the catalyst and an aqueous phase containing the substrate, 2-butyne-1,4-diol (**114**) (Figure 1.40).

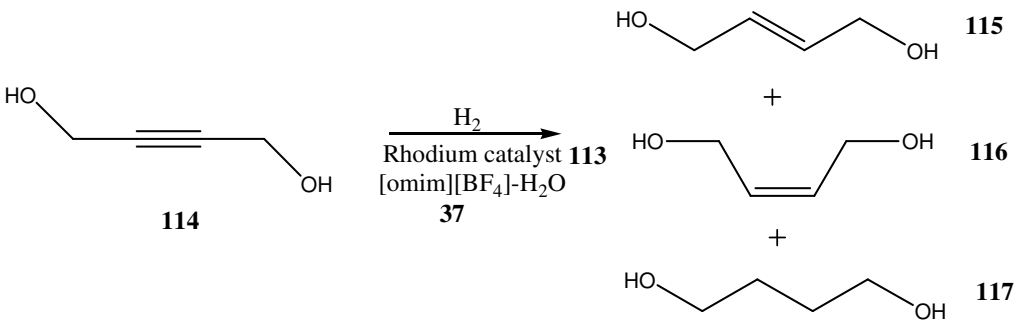


Figure 1.40 Hydrogenation of butyne-1,4-diol

At room temperature, the phases were immiscible; however the reaction was carried out at 80 ºC thus allowing the reaction to be homogeneous. Facile separation of the reduced products from the catalyst/IL phase was obtained by cooling the reaction. The products dissolved in the aqueous phase were isolated and reuse of the IL/catalyst system demonstrated. The limitations of this system were shown with maleic acid, where the reduced product, succinic acid, was soluble in both the IL and aqueous phase.

Wolfson *et al.*[87] used [bmim][PF_6] (**27**) as reaction medium in the hydrogenation of 2-cyclohexen-1-one (**118**) with Wilkinson's catalyst (**119**) (Figure 1.41).

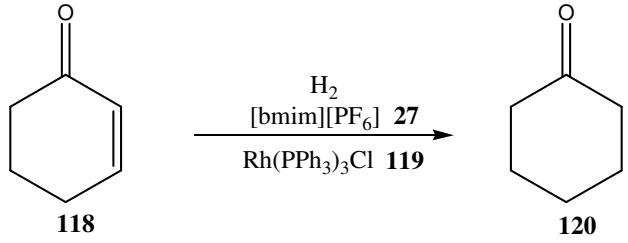


Figure 1.41 Hydrogenation of 2-cyclohexen-1-one

As water was shown to enhance the activity of Wilkinson's catalyst (**119**), it was used in the biphasic hydrogenation of the substrate (**118**). Diethyl ether and hexane were screened but demonstrated low hydrogenation activity. The conversion to cyclohexanone (**120**) increased from 4 % in diethyl ether and 7 % in hexane to 26 % in water.

Scurto *et al.*[88] used biphasic hydrogenation conditions with $scCO_2$ and a rhodium catalyst (**121**) for the hydrogenation of 2-vinyl-naphthalene (**122**) (Figure 1.42).

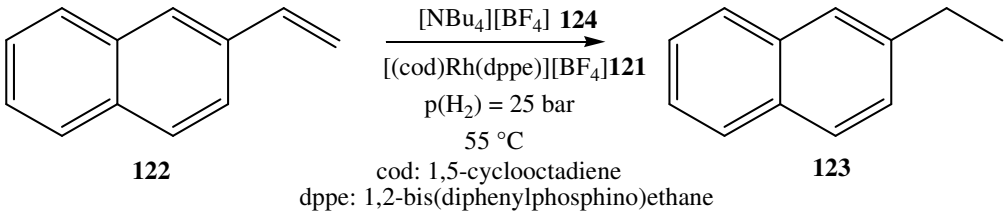


Figure 1.42 Hydrogenation of 2-vinyl-naphthalene

[TBA][BF_4] (**124**) was pressurised with CO_2 to give a high melting point depression of the salt for subsequent use as a reaction solvent in the liquid phase. Conversions for the first three runs using the IL were high (> 93 %). The authors explained that the drop in conversion to 62 % by the fifth run may have been due to accidental oxygen introduction or loss of catalyst during the recycling procedure.

Suarez *et al.*[89] used a ruthenium catalyst ($RuCl_2(TPPMS)_3(DMSO)$; TPPMS: triphenylphosphine monoosulfonate **125**) immobilised in [bmim][PF_6] (**27**) for the biphasic hydrogenation of 1-hexene (**126**). They investigated the effect of different parameters on the hydrogenation rate and conversion. It was observed that up to a certain temperature, the viscosity of the IL decreased therefore the conversion rate increased, however above 120 ºC, decomposition of the catalyst was observed. Increasing the pressure also increased the percentage of conversion, until it levelled off at a pressure of higher than 500 psi. Overall, greater than 99 % conversion was observed for the hydrogenation of 1-hexene in the IL, however upon recycling, the total conversion level decreased (70 % after six reuses). Two other substrates were also investigated (cyclohexene (**127**) and crotonaldehyde (**128**)). 34 % conversion was achieved with cyclohexene (**127**), while only 25 % was achieved using crotonaldehyde (**128**), with 1-butanol formed as the only product.

The tailoring of ILs to carry out a specific role together with acting as reaction medium is emerging as an efficient way to limit the number of reagents required in a chemical reaction. The synthesis of a task-specific imidazolium IL (1-(*N,N*-dimethylaminoethyl)-2,3-dimethylimidazolium trifluoromethanesulfonate) (**129**) was carried out in three steps to yield a basic IL for the hydrogenation of carbon dioxide (**130**) to form formic acid (**131**) (Figure 1.43).[90]

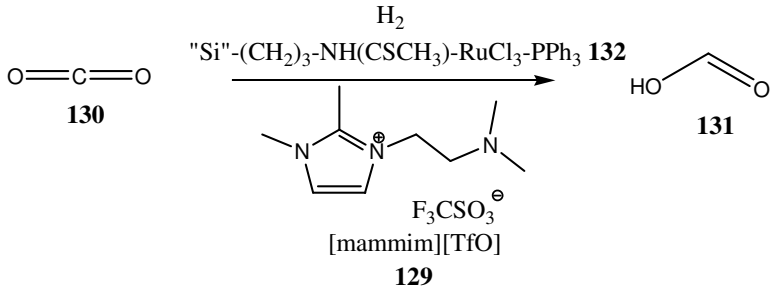
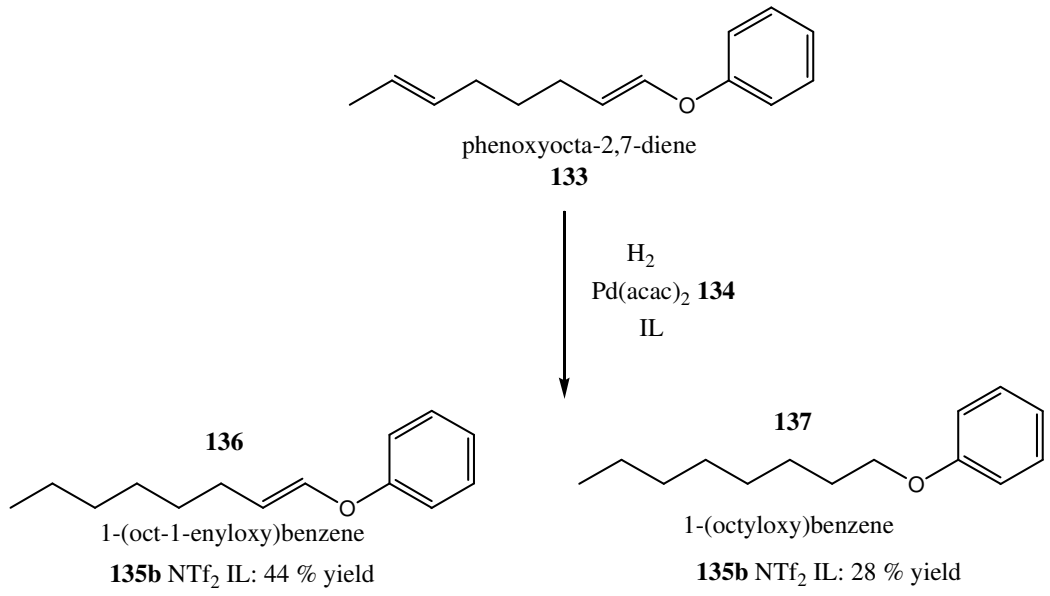


Figure 1.43 Hydrogenation of carbon dioxide

The IL acts as a base for the promotion of the hydrogenation reaction. A ruthenium catalyst immobilised on silica (**132**) was used as heterogeneous catalyst phase dispersed in a solution of aqueous IL. It was shown that water was necessary for the success of the reaction, the reason being presumed to be to lower the viscosity of the IL. The task-specific basic IL (**129**) favoured the formation of the product, the formation of a salt with the latter driving the reaction. TOFs as high as 103 h^{-1} were reached. An increase in H_2 and CO_2 pressure together with increasing the amount of IL used was found to favour higher TOFs. The process was shown to be suitable for recycling procedures, with no significant reduction in TOF being observed after four recycles.

Bouquillon *et al.*[18] used novel ILs, including a readily biodegradable IL for the hydrogenation of phenoxyocta-2,7-diene (**133**).[91] Impressive conversions were obtained for the hydrogenation of the diene substrate using a palladium catalyst (**134**) (Figure 1.44). The biodegradable [$OctOSO_3$] imidazolium IL (**135f**) displayed superior conversion (85 %) to the [NTf_2] derivative (**135d**) (75 %). The potential for reuse of the IL/catalyst system was portrayed by the recycling of the [$OctOSO_3$] system albeit with a significant decrease in conversion to 55 % observed.



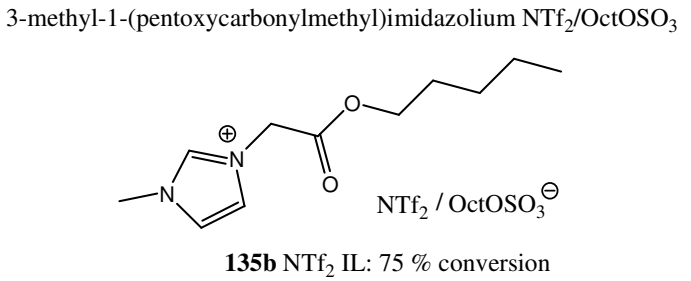
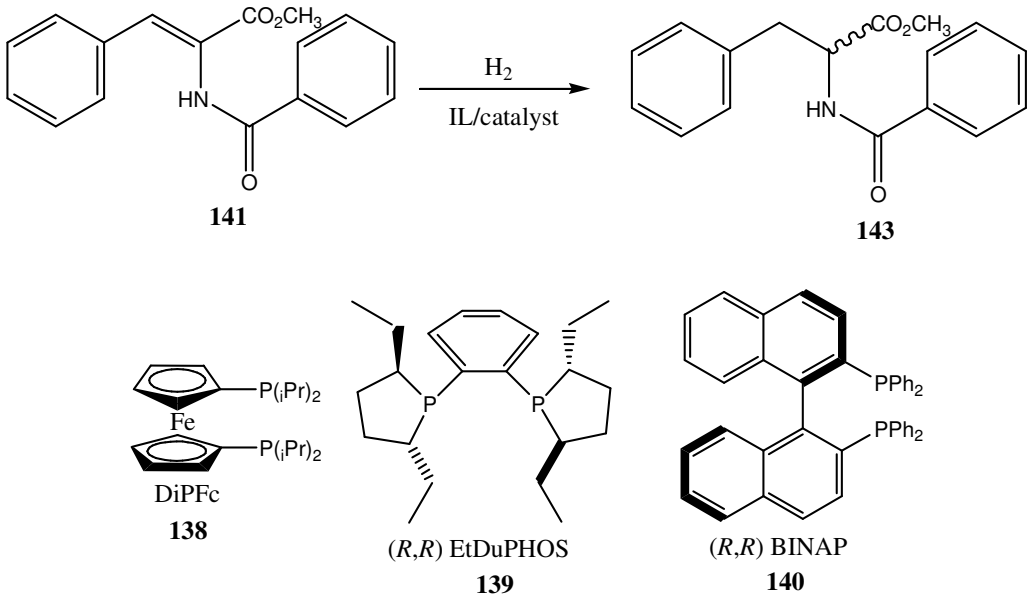


Figure 1.44 Hydrogenation of phenoxyocta-2,7-diene

1.4.3 Asymmetric Hydrogenation in ILs

Asymmetric hydrogenation is one of the main pathways for the synthesis of enantiomerically pure products.[92] For the greater part, the source of chiral induction originates from chiral ligands coordinated to a metal catalyst. [93]It has been demonstrated that tertiary phosphine stabilised-rhodium, ruthenium and iridium catalysts are the most likely to induce substantial enantiomeric excess in the formation of the chiral product.[94-96] Extensive research into the hydrogenation of prochiral substrates in ILs has been carried out over the past few years. The majority of this work has employed ruthenium or rhodium based catalysts. Ruthenium and rhodium catalysts, DiPFc-Rh (**138**), EtDuPHOS-Rh (**139**) and BINAP-Ru (**140**), were compared by Boyle *et al.*[97] The hydrogenation of α-benzamido cinnamate (**141**) (Figure 1.45) in ILs, [bmim][BF_4] (**31**) and [emim][OTf] (**142**), without the use of a co-solvent was carried out. As the

conversion was negligible using the IL [bmim][BF_4] (**31**) (0 - < 2 %), the second IL was the focus of the following reactions, eventually giving a conversion of 95 % and 89 % ee using Ru-**140** as catalyst.



141 **143**

DiPFc
138

(*R*,*R*) EtDuPHOS
139

(*R*,*R*) BINAP
140

Figure 1.45 Hydrogenation of α-benzamido cinnamate

1.4.3.1 Hydrogenation using rhodium catalysts

Schmitkamp *et al.*[98] investigated the hydrogenation of dimethyl itaconate (**144**) and methyl 2-acetamidoacrylate (**145**) (Figure 1.46) using [NTf_2] CILs derived from L-proline (**146**) and L-valine (**147**) and a rhodium catalyst with tropoisomeric ligands (**148** and **149**).

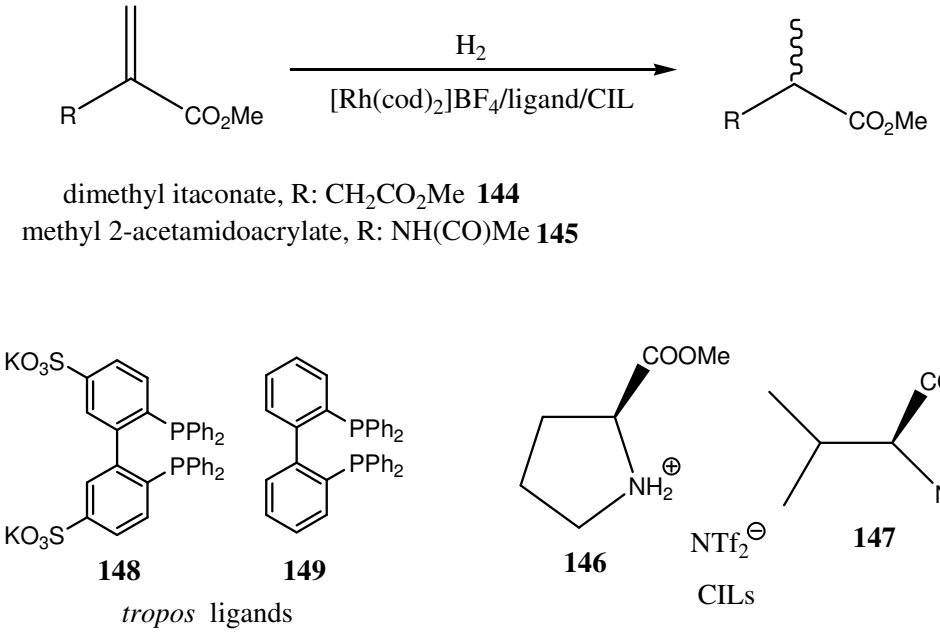
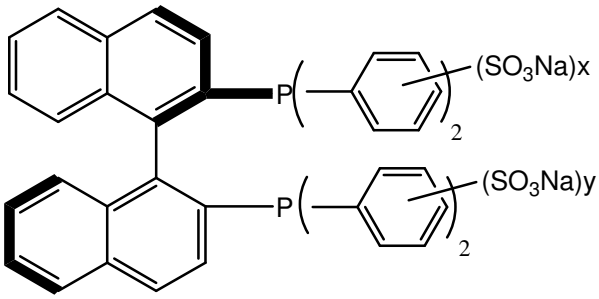


Figure 1.46 Hydrogenation of prochiral substrates using CILs and a rhodium catalyst

They investigated the effects of using different CILs (**146** and **147**) and the effect of sulfonated ligands on the conversion and enantioselectivity of the reactions. For the hydrogenation of methyl 2-acetamidoacrylate (**145**), using the sulfonated ligand (**148**), 49 (*S*) % ee was obtained using **146**, where a racemic mixture was obtained under the same conditions using **147**. This group thus used **146** for all subsequent hydrogenations. Concerning the acrylate substrate, considerable enantiomeric excess was obtained for the (*S*) enantiomer when triethylamine was used as an additive in the reaction (69 %). Using dimethyl itaconate as the substrate, the amine additive was again found to increase the enantioselectivity (from 20 (*R*) % ee without additive to 29 (*R*) % ee with additive). The sulfonate groups present in the *tropos* ligand (**138**) were shown to be essential for increased enantioselectivity for both substrates. Enantioselectivity decreased dramatically when the unsulfonated ligand (**149**) was employed. Converting from **148** to **149**, a drop in enantioselectivity was observed for methyl 2-acetamidoacrylate (**145**), from 49 (*S*) to 28 (*S*) % ee, and using triethylamine as additive, from 69 (*S*) to 52 (*S*) % ee. Recycling of the system was proven possible by product extraction using $scCO_2$. The recycling procedure showed a compromise in conversion from > 99 % for the first run to 57 % upon run three. Enantioselectivity was also moderately compromised during the recycling procedure, decreasing from 69 % ee upon run one to 52 % ee over three cycles.

Sulfonated ligands were also investigated by She *et al.*[99] for investigation into the hydrogenation of dimethyl itaconate (**144**). A chiral rhodium complex containing water soluble BINAPS ligands (**150**) (Figure 1.47) was used for the reaction in ILs [bmim][BF_4] (**31**) and [PF_6] (**27**).



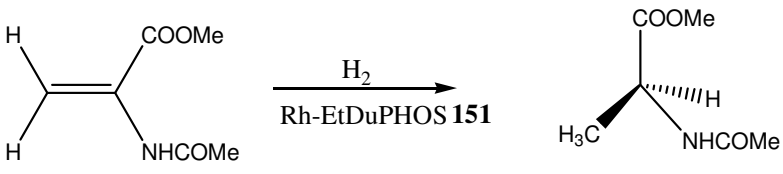
150

(*R*)-BINAPS: (*R*)-BINAP-*n*SO_3Na, *n* = x+y = 3-4

Figure 1.47 Chiral rhodium complex

An IL/IPA biphasic system was used and conversions up to 100 % were obtained, with moderate enantioselectivities (49 - 70 %). Catalytic activity began decreasing however after four runs of recycling the system, but the authors found that the addition of fresh ligand to the catalyst re-established its performance.

[Bmim][PF_6] (**27**) was used as reaction medium in the asymmetric hydrogenation of methyl 2-acetamidoacrylate (**145**) with a rhodium catalyst (Rh-EtDuPHOS) (**151**) (Figure 1.48).[87]

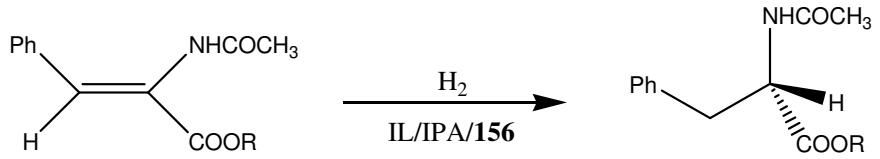


145 **151** **152**

Figure 1.48 Hydrogenation of 2-acetamidoacrylate

The reaction did not proceed when performed in the IL alone. To enable the recycling of the catalyst immobilised in the IL, solvents immiscible in the IL were screened. Water gave the highest conversion (68 %) compared to hexane (0 %), diethyl ether (12 %) and IPA (31 %). However the enantioselectivity remained the same (95 -96 % ee) for the three solvents that gave conversion. The authors postulate water is the superior solvent due to greater mixing with the IL phase, with the water droplets dispersed more effectively in the IL medium than the organic solvents.

The hydrogenation of (Z)-α-acetamidocinnamic acid (**153**) and methyl-(Z)-α-acetamidocinnamate (**154**), was carried out in the ILs, [bmim][BF_4] (**31**), [bmim][PF_6] (**27**) and [mbpy][BF_4] (**155**) using a rhodium catalyst ([Rh(COD)(DIPAMP)][BF_4]) (**156**) (Figure 1.49).[100]



153 R=H
154 R=Me

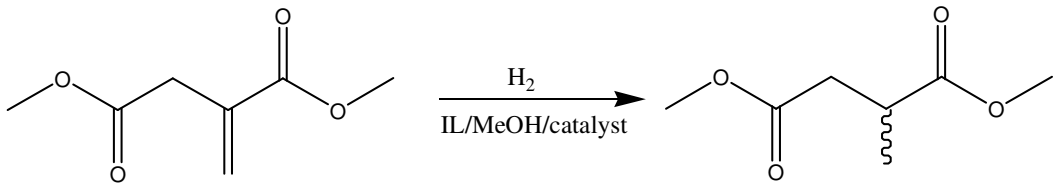
153a R=H
154a R=Me

Figure 1.49 Hydrogenation of (Z)-α-acetamidocinnamic acid and methyl-(Z)-α-acetamidocinnamate

In this case, IPA was used as a co-solvent in a biphasic system to facilitate recycling of the catalyst phase. A study of the temperature on the enantioselectivity showed this value to peak at 55 °C. At 5 bar H_2 pressure, conversion percentage was above 97 % for the both substrates in [bmim][BF_4] (**31**) and [bmim][PF_6] (**27**). Enantioselectivity was also good, with enantioselectivities between 71-92 % being obtained. Frater *et al.*[100] showed the catalyst system to retain activity up to the fourth recycle, after which the conversion decreased slightly, with enantioselectivity remaining constant for each subsequent recycle.

1.4.3.2 Hydrogenation using ruthenium catalysts

Using methanol as co-solvent, ILs were tested for the hydrogenation of dimethyl itaconate (**144**) to dimethyl methylsuccinate (**157**) (Figure 1.50), using the catalyst (*R*)-Ru-BINAP ((*R*)-Ru-**140**), at near ambient temperature (35°C), and 20 bar H_2.[101]

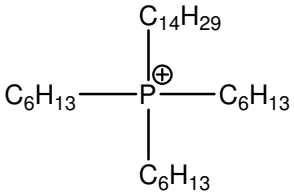


144 **157**

Figure 1.50 Hydrogenation of dimethyl itaconate

In order to recycle the system, organic solvent nanofiltration (OSN) was used to separate the catalyst and IL from the product. Recycling of their methanol/CyPhos101 (**158**) system was achieved eight times with no loss in enantioselectivity or catalyst

activity. Compared to using pure methanol as solvent, the methanol/CyPhos101 (**158a**) and methanol/[TBA][Cl] (**159**) systems showed increased enantioselectivities, ranging from 75 % in pure methanol, to 95 % in the co-solvent system. The authors showed the dependence of catalytic activity on the anion of the IL. Using CyPhos101 (**158a**), good enantioselectivities and process yields were obtained, however when the anion was changed, in the case of CyPhos103 (**158b**), 110 (**158c**) and 111 (**158d**) (Figure 1.51), no improvement in ee or process yield was observed.



Anions $^{\ominus}$

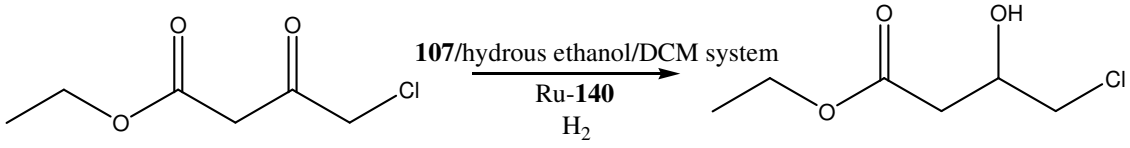
CyPhos101: Cl **a**
Cyphos103: decanoate **b**
Cyphos110: PF_6 **c**
Cyphos 111: BF_4 **d**

Cation tetradecyl(trihexyl)phosphonium

158

Figure 1.51 CyPhos ILs

The hydrogenation of ethyl 4-chloro-3-oxobutyrate (**160**) to give ethyl 4-chloro-3-hydroxy butyrate (**161**) (Figure 1.52) was investigated by Starodubtseva *et al.*[102] using a Ru-BINAP (Ru-**140**) catalyst in various IL systems.



ethyl 4-chloro-3-oxobutyrate

160

ethyl 4-chloro-3-hydroxy butyrate

161

100% conversion

92% ee

Figure 1.52 Hydrogenation of 4-chloro-3-oxobutyrate

Hydrogenation results were poor using the ILs neat or in combination with an aprotic co-solvent. Starodubtseva then examined the use [bmim][PF_6] (**27**), [bmim][NTf_2] (**107**) and [TEA][Br] (**162**) with protic solvents, in particular ethanol. It was found that water content was also important with superior results obtained for wet ethanol compared to anhydrous ethanol. The anhydrous ethanol formed a biphasic system with the IL and catalyst. When wet ethanol was used a homogeneous mixture with the IL/catalyst system formed. Good conversion, selectivity and enantioselectivity were observed in the case of the [bmim][NTf_2] (**107**)/hydrous ethanol/DCM system (100, 100, and 92 %

respectively). The conversion however decreased by more than half its original value (to 46 %) upon the third run. Selectivity remained excellent (100 %) for all three runs, and the enantioselectivity only slightly decreased (85 % for run three). Using the [TEA][Br] (**162**) IL as an example, the authors showed increasing temperature to be important for enhanced catalyst activity. By increasing the temperature from 30 °C (conversion = 42 %, selectivity = 93 %, ee = 85 %), to 70 °C (conversion = 100 %, selectivity = 100 %, ee = 96 %) improvements in catalytic performance were evident.

With their novel ruthenium catalyst $(RuCl_2(TPPTS)_2]_2$-(1*S*,2*S*)-DPENDS-KOH; TPPTS: P(*m*-$C_6H_4SO_3Na)_3$ (**163**) and DPENDS: (1*S*,2*S*)-1,2-diphenyl-1,2-ethylene diamine sulfonate disodium) (**164**), Xiong *et al.*[103] carried out the hydrogenation of various aromatic ketones using a selection of ILs ([emim] (**165**), [bmim] (**166**), [omim] (**167**) and [dodecylmim] (**168**) [*p*-$CH_3C_6H_4SO_3$] and [bmim][BF_4] (**31**) and [PF_6] (**27**)) (Figure 1.53).

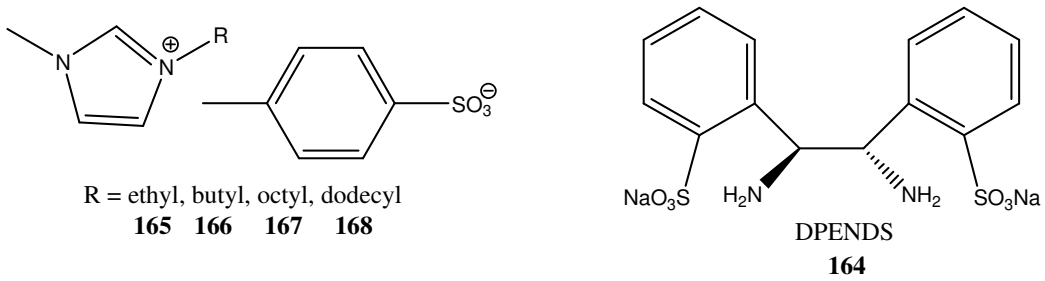
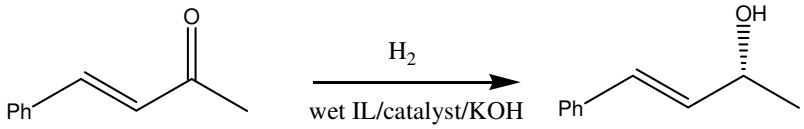


Figure 1.53 *Para*-sulfonate imidazolium ILs and DPENDS

The best results were obtained using the aromatic anionic ILs with a dramatic decrease in conversion and enantioselectivity being obtained with the [bmim][PF_6] (**27**) IL. The authors attributed this fact to be due to hydrophobicity of the IL hindering the activity of the hydrophilic catalyst. A decrease in enantioselectivities was observed with an increase in alkyl chain length of the cation of the IL. Various parameters were investigated as a function of catalyst activity in the IL that showed the most promising results, namely [bmim][*p*-$CH_3C_6H_4SO_3$] (**166**). It was seen that increasing temperature brought about a decrease in enantioselectivity. An increase in the amount of base added (KOH) significantly increased the conversion and the enantioselectivity, as did the addition of (1*S*, 2*S*)-DPENDS. The best catalyst precursor was shown to be $[RuCl_2(TPPTs)_2]_2$ with a conversion of 100 % and enantioselectivity of 79.2 % obtained. In total, nine aromatic ketones were tested, giving good conversions (68.0 - 100 %) and moderate enantioselectivities (40.0 – 80.6 %). Recycling of the IL/catalyst system over nine runs showed conversions ranging between 100 % and 68.7 %, where

even the lowest value of 68.7 % was redeemed by the addition of more KOH. The same group[104] used their novel catalyst for the hydrogenation of α, β-unsaturated ketones using ILs. Using benzalacetone (**169**) as a reference substrate (Figure 1.54), they found that the lipophilic chains on the cations of the ILs influenced the enantioselectivity.



169 **170**

Figure 1.54 Selective hydrogenation of benzalacetone

Although selectivity was always high towards the unsaturated alcohol (**170**) with all ILs tested, enantioselectivity can be seen to decrease as alkyl chain length is increased (from 71.8 % ee for [emim] to 59.9 % for the [dodecyl] chain).

This group also investigated the effect of base and water content on the reaction. 100 % conversion was reached using strong bases such as NaOH and KOH, while only 4.6 % conversion was obtained in the presence of K_2CO_3. Higher enantioselectivies were also observed with the stronger hydroxide bases (ca. 70%) compared to 58.7% ee for K_2CO_3. Water was found to be a valuable co-solvent, and optimised conditions led to 100 % conversion, 100 % chemoselectivity and 75.9 % enantioselectivity. When other α, β-unsaturated ketones were investigated, promising results were also obtained. Hydrogenation of 2-cyclohexen-1-one (**118**) gave good conversion (100 %) and chemoselectivity (94.1 % for the unsaturated alcohol), however with a moderate ee value (48.1 %). On the other hand, 4-methyl-3-penten-2-one (**171**) showed good enantioselectivity (84.7 %) and chemoselectivity (84.9 %), however with only poor conversion (29.1 %). The IL/catalyst system was efficiently recycled eight times with conversion always above 87.9 % from an initial 100 % for the first run. A slight reduction was observed for the chemoselectivity (from 100 % to 99.1 %) and the enantioselectivity remained almost constant for each successive recycle.

Lam *et al.*[105] used a ruthenium catalyst with a dipyridylphosphine ligand (P-Phos) (**172**) for the asymmetric hydrogenation of α- and β-keto esters (Figure 1.55).

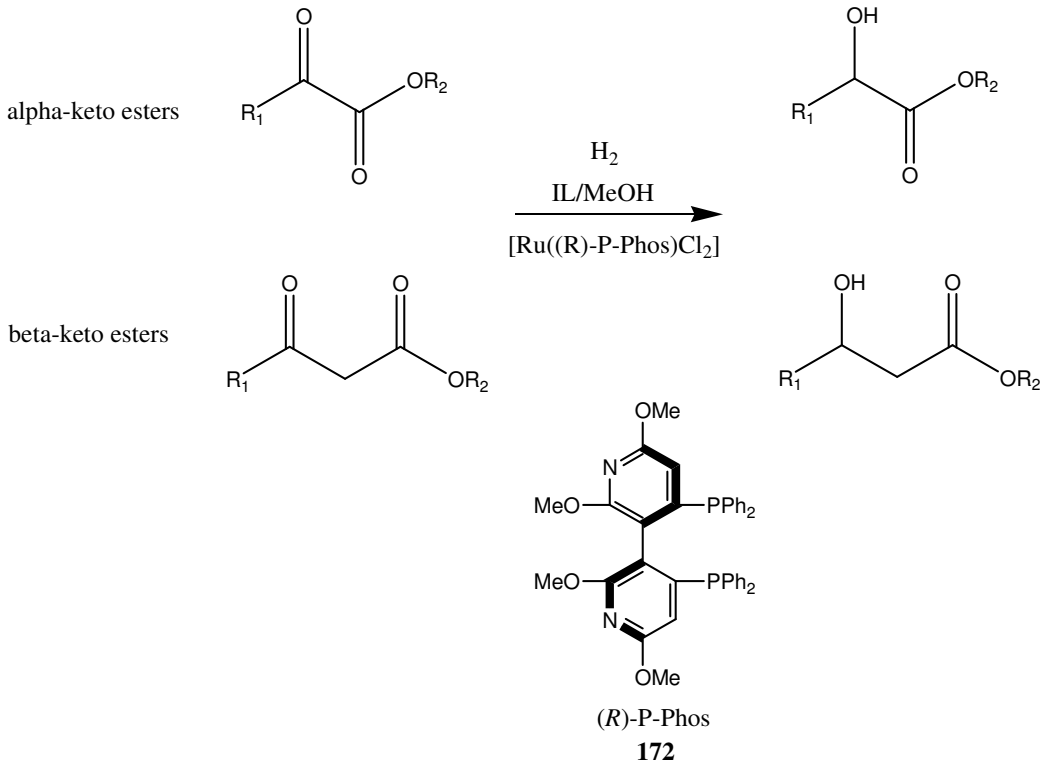


Figure 1.55 Asymmetric hydrogenation of α- and β-keto esters

Methyl pyruvate (**173**) was taken as an example from the α-keto esters and the hydrogenation was carried out with **172** and a standard ruthenium BINAP catalyst. It was found that a co-solvent was a necessity for these hydrogenations, as using the IL on its own as reaction solvent gave negligible conversions. Methanol was used in equal volumes as co-solvent and using **172** tethered to the ruthenium catalyst, good conversions were obtained (73 and 95 % conversion for [bmim][PF_6] (**27**) and [bmim][BF_4] (**31**) respectively) with good enantioselectivity (86 and 83 % ee). Enantioselectivies decreased when moving to the BINAP ligand, however conversions achieved were higher. A range of α-keto esters were tested, conversions ranging from 18 % in [bmim][BF_4] (**31**), however to 65 % for the same substrate using the [bmim][PF_6] (**27**) IL. The best results in terms of conversion (65 %) and enantioselectivity (93 %) were obtained with the substrate methyl 2-oxo-2-phenylacetate (**174**) in the [bmim][PF_6] (**27**) IL. Methyl acetoacetate (**175**) was used as a reference substrate for the hydrogenation of the β-keto esters, giving conversions and enantioselectivity values greater than 98 % for **172** as well as the BINAP ligand. In general, the range of β-keto esters subjected to hydrogenation with the ruthenium P-Phos catalyst displayed improved results, with most conversions reaching at least 70 %, enantioselectivity values also being as high as greater than 99 %. The hydrogenation of

methyl acetoacetate (**175**) was investigated in the two ILs for recycling ability. Both IL systems were recycled nine times with similar results although the conversion had dramatically decreased by run nine for both ILs (39 % for [BF_4] and 49 % for [PF_6]), enantioselectivities did not fall below 94 % for both ILs over the nine runs.

1.5 General conclusion

With increased environmental awareness throughout the chemical industry, the use of hydrogen gas for hydrogenation reactions is especially popular as it is a clean reducing agent. Coupled with the use of ILs as safer alternatives to VOCs as reaction solvents, hydrogenation reactions can be very attractive as clean, 'green' synthetic methods. The solubility of gaseous H_2 has been shown to be lower in ionic liquids than in common organic solvents, however mass transfer effects of the gas in the IL are high enough in some cases to overcome this limitation. The availability of the hydrogen at the catalyst site may be replenished due to the relative ease of mass transfer of the gas in the solvent, leading to high conversions. Recyclability of the catalyst system is a major factor in the potential use of the IL. ILs provide a stabilising media for catalysts and facilitate their immobilisation therefore rendering possible recycling procedures. IL/catalyst systems have been shown to be easily recycled in numerous cases while retaining their activity. Biphasic hydrogenations have also demonstrated recyclability, the substrates and products residing in a separate phase to the IL and catalyst. A particularly efficient method that has been outlined is where the substrate is dissolved in the IL phase, and the reduction products form a second phase, thus facilitating clean, simple decantation of the desired product from the IL phase. However if the products are also soluble in the IL phase and a second organic solvent is needed for extraction from the mixture, the requirement for the harmful VOC solvent detracts from the benefit of using the IL unless the recycling ability of the IL is considerable. Although ILs are duly attracting a staggering magnitude of attention, their benefits must be balanced with their limitations, and these elements investigated if the solvents are to replace volatile organic solvents on an industrial scale. Although the principal ILs studied for hydrogenation reactions have been the popular [bmim][BF_4] (**31**) and [bmim][PF_6] (**27**), novel ILs have been synthesised and studied as reaction media for these reactions. The cost of synthesis of these novel ILs should be at the forefront of our minds if these solvents are to be used on a large scale. A predominant factor contributing to cost

reduction, and also a possible way forward, may be the use of the supported systems, thus requiring a smaller quantity of the IL.

Recycling of the IL is also important. An IL which can only maintain its required performance for 2-5 cycles has limited use. A significantly higher number of effective recycles is one of the major goals for this research area.

The ‘greenness’ of ILs has been disputed due to their possible persistence and toxicity in the environment. It is not only the cost and performance that should be a component in designing ILs for use in hydrogenation technologies, but toxicity, bioaccumulation and biodegradability should be given equal merit to the process selection before the IL development and use in large scale chemical synthesis.

1.6 Bibliography

1 D. Armstrong, A. Anderson, *U. S. Pat.*.WO2008095064, 2008.

2 A. Arce, M. Earle, S. Katdare, H. Rodriguez and K. Seddon, *Phys. Chem. Chem. Phys.,* 2008, **10**, 2538.

3 P. Wasserscheid and P. Schultz, in *Ionic Liquids in Synthesis*, WILEY-VCH, 2008, p. 369.

4 D. Upadhyaya, A. Barge, R. Stefania and G. Cravotto, *Tetrahedron Lett.,* 2007, **48**, 8318.

5 H. Oskooie, M. Heravi, A. Sadnia, F. Behbahani and F. Jannati, *Chinese Chemical Letters,* 2007, **18**, 1357.

6 CAS Registry Number 78041-07-3

7 J. Wilkes, *Green Chem.,* 2002, **4**, 73.

8 P. Walden, *Bull. Acad. Imper. Sci. (St. Petersburg),* 1914, 1800.

9 T. Welton, *Chem. Rev.,* 1999, **99**, 2071.

10 J. D. Holbrey and K. R. Seddon, *Clean Products and Processes 1,* 1999, 223.

11 J. Clarke and D. Macquarrie, *Handbook of Green Chem. and Technology*, Oxford, 2002.

12 Z. Zhang, D. Zhao, Y. Liao, *Clean,* 2007, **35**, 42.

13 J. Ranke, S. Stolte, R. Stormann, J. Arning and B. Jastorff, *Chem. Rev.,* 2007, **107**, 2183.

14 M. Rosen, F. Li, S. Morrall and D. Versteeg, *Environ. Sci. Technol.,* 2001, **35**, 954.

15 D. J. Couling, R. J. Bernot, K. M. Docherty, J. K. Dixon and E. J. Maginn, *Green Chem.,* 2006, **8**, 82.

16 J. Ranke, K. Molter, F. Stock, U. Bottin-Weber, J. Poczobutt, J. Hoffmann, B. Ondruschka, J. Filser and B. Jastorff, *Ecotoxicology and Environmental Safety,* 2004, **58**, 396.

17 J. Pernak, K. Sobaszkiewicz and I. Mirska, *Green Chem.,* 2002, **5**, 52.

18 J. Pernak, I. Goc and I. Mirska, *Green Chem.,* 2004, **6**, 323.

19 K. M. Docherty and C. F. Kulpa Jr, *Green Chem.,* 2005, **7**, 185.

20 Romero, A. Santos, J. Tojo and A. Rodriguez, *Journal of Hazardous Materials,* 2008, **151**, 268.

21 M. T. Garcia, N. Gathergood and P. J. Scammells, *Green Chem.,* 2004, **7**, 9.

22 D. Pol, http://tinyurl.com/6yjc7g 2007.

23 S. Stolte, S. Abdulkarim, J. Arning, A. K. Blomeyer-Nienstedt, U. Bottin-Weber, M. Matzke, J. Ranke, B. Jastorff and J. Thoming, *Green Chem.,* 2007, **10**, 214.

24 M. Matsumoto, K. Mochiduki, K. Fukunishi and K. Kondo, *Separation and Purification Technology,* 2004, **40**, 97.

25 M. Matsumoto, K. Mochiduki and K. Kondo, *Journal of Bioscience and Bioengineering,* 2004, **98**, 344.

26 Kathryn M. Docherty, Susanne Z. Hebbeler, Charles F. Kulpa, Jr., *Green Chem.,* 2006, **8**, 560.

27 Wells and V. Coombe, *Org. Process Res. Dev.,* 2006, **10**, 794.

28 R. J. Bernot, M. A. Brueseke, M. A. Evans-White and G. A. Lamberti, *Environmental Toxicology and Chemistry,* 2005, **21**, 87.

29 B. Jastorff, R. Stormann, J. Ranke, K. Molter, F. Stock, B. Oberheitmann, W. Hoffmann, J. Hoffmann, M. Nuchter, B. Ondruschka and J. Filser, *Green Chem.,* 2003, **5**, 136.

30 M. K. Agrawal, D. Bagchi and S. N. Bagchi, *Hydrobiologia,* 2001, **464**, 37.

31 L. R. Shugart, *Ecotoxicology: A Hierarchical Treatment,* 1996, 133.

32 P. Nockemann, B. Thijs, K. Driesen, C. Janssen, K. Van Hecke, L. Van Meervelt, S. Kossmann, B. Kirchener and K. Binnemans, *J. Phys. Chem. B,* 2007, **111**, 5254.

33 Latala, P. Stepnowski, M. Nedzi and W. Mrozik, *Aquatic Toxicology,* 2005, **73**, 91-98.

34 Cho, T. P. Pham, Y. Jeon and Y. Yun, *Green Chem.,* 2008, **10**, 67.

35 Cho, t. Pham, Y. Jeon, K. Vijayaraghhavan, W. Choe and Y. Yun, *chemosphere,* 2007, **69**, 1003.

36 T. Pha, C. Cho, J. Min and Y. Yun, *Jounal of Bioscience and Bioengineering,* 2008, **104**, 425.

37 G. Lamberti and K. Kulacki, *Green Chem.,* 2008, **10**, 104.

38 S. Stolte, J. Arnig, U. Bottin-Weber, A. Muller, W. Pitner, U. Welz-Biermann, B. Jastorff and J. Ranke, *Green Chem.,* 2007, **9**, 760.

39 M. Matzke, S. Stolte, K. Thiele, T. Juffernholz, J. Arning, J. Ranke, U. Welz-Biermann and B. Jastorff, *Green Chem.,* 2007, **9**, 1198.

40 B. Jastorff, K. Molter, P. Behrend, U. Bottin-Weber, J. Filser, A. Heimers, B. Ondruschka, J. Ranke, M. Schaefer, H. Schroder, A. Stark, P. Stepnowski, F. Stock, R. Stormann, S. Stolte, U. Welz-Biermann, S. Ziegert and J. Thoming, *Green Chem.,* 2005, **7**, 362.

41 Vogel, http://tinyurl.com/5rwtp7

42 Gardenstuff Ltd., http://tinyurl.com/6ldjq8 2007.

43 P. Balczewski, B. Bachowska, T. Bialas, R. Biczak, W. Wieczorek and A. Balinska, *Agricultural and Food Chemistry,* 2007, **55**, 1881.

44 Stefan Stolte, Jurgen Arning, Ulrike Bottin-Weber, Marianne Matzke, Frauke Stock, Karen Thiele, Marc Uerdingen, Urs Welz-Biermann, Bernd Jastorff and Johannes Ranke, *Green Chem.,* 2006, **8**, 621.

45 J. Ranke, A. Muller, U. Bottin-Weber, F. Stock, S. Stolte, J. Arning, R. Stormann and B. Jastorff, *Ecotoxicology and Environmental Safety,* 2007, **67**, 430.

46 J. Salminen, N. Papaiconomou, R. A. Kumar, J. Lee, J. Kerr, J. Newman and J. prausnitz, *Fluid Phase Equilibria,* 2007, **261**, 421.

47 X. Wang, A. Ohlin, Q. Lu, Z. Fei, J. Hu and P. Dyson, *Green Chem.,* 2007, **9**, 1191.

48 Garcia, E. Tojo, J. Tojo, M. Teijeira, F. Rodriguez, M. Gonzalex and V. Martinez, *Green Chem.,* 2008, **10**, 508.

49 F. Stock, J. Hoffmann, J. Ranke, R. Stormann, B. Ondruschka and B. Jastorff, *Green Chem.,* 2004, **6**, 286.

50 A.C. Skladanowski, P. Stepnowski, K. Kleszczynski, B. Dmochowska, *Environmental Toxicology and Pharmacology,* 2005, **19**, 291.

51 R. P. Swatloski, J. D. Holbrey, S. B. Memon, G. A. Caldwell, K. A. Caldwell and R. D. Rogers, *Chem. Commun..,* 2004, 668.

52 R. J. Bernot, E. E. Kennedy and G. A. Lamberti, *Environmental Toxicology and Chemistry,* 2005, **24**, 1759.

53 C. Pretti, C. Chiappe, D. Pieraccini, M. Gregori, F. Abramo, G. Monni and L. INtorre, *Green Chem.,* 2005, **8**, 238.

54 D. W. Connell, *Basic Concepts of Environmental Chemistry*, Taylor and Francis, 2005, p. 60.

55 N. Gathergood, M. T. Garcia and P. J. Scammells, *Green Chem.,* 2004, **6**, 166.

56 R. A. Rapaport and W. S. Eckhoff, *Environ. Toxicol. Chem,* 1990, **9**, 1245.

57 P. H. Howard, R. S. Boethling, W. Stiteler, W. Meylan and J. Beauman, *Sci. Total Environ.,* 1991, 109.

58 R. S. Boethling, *Cationic Surfactants, Surfactant Science* Series, 1994, **53**, 95.

59 R. S. Boethling, *Designing Safer Chemicals*, *ACS Symposium Series*, 1996, **640**, 156.

60 J. Waters, H. H. Kleiser, M. J. How, M. D. Barratt, R. R. Birch, R. J. Fletcher, S. D. Haugh, S. G. Hales, S. J. Marshall and T. C. Pestell, 1991, **28**, 460.

61 K. Docherty, J. Dixon and C. Kulpa, *Biodegradation,* 2007, **18**, 481.

62 J. Harjani, R. Singer, T. Garcia and P. Scammells, *Green Chem.,* 2008, **10**, 436.

63 D. Seebach, H.A. Oei, *Angew. Chem.,* 1975, **14**, 634.

64 C. Baudequin, J. Baudoux, J. Levillain, D. Cahard, A. C. Gaumont and J. C. Plaquevent, *Tetrahedron: Asymmetry,* 2003, **14**, 3081.

65 C. Baudequin, D. Bregeon, J. Levillain, F. Guillen, J. C. Plaquevent and A. C. Gaumont, *Tetrahedron: Asymmetry,* 2005, **16**, 3921.

66 J. Ding and D. W. Armstrong, *Chirality,* 2005, **17**, 281.

67 X. Chen, X. Li, A. Hu and F. Wang, *Tetrahedron: Asymmetry,* 2008, **19**, 1.

68 Winkel, P. Reddy and R. Wilhelm, *Synthesis,* 2008, **7**, 999.

69 M. J. Earle, P. B. McCormac and K. R. Seddon, *Green Chem.,* 1999, **1**, 23.

70 X. Xin, X. Guo, H. Duan, Y. Lin and H. Sun, *Catalysis Communications,* 2007, **8**, 115.

71 Zhu, T. Jiang, D. Wang, B. Han, L. Liu, J. Huang, J. Zhang and D. Sun, *Green Chem.,* 2005, **7**, 514.

72 L. Da-Peng, X. Xin, D. Hai-feng, Y. Yan-zhen, G. Han, L. Ying-jie and X. Jia-ning, *Chem. Res. Chinese Universities,* 2008, **24**, 36.

73 J. J. Jodry, K. Mikami, *Tetrahedron Lett.,* 2004, **45**, 4429.

74 Zhiming Wang, Qiang Wang,Yu Zhang and Weiliang Bao, *Tetrahedron Lett.,* 2005, **46**, 4657.

75 T. Biedroń and P. Kubisa, *Polymer International,* 2003, **52**, 1584.

76 L. Branco, P. Gois, N. Lourenco, V. Kurteva and C. Afonso, *Chem. Commun.,* 2006, 2371.

77 C. R. Allen, P. L. Richard, A. J. Ward, L. G. A. van de Water, A. F. Masters, T. Maschmeyer, *Tetrahedron Lett.,* 2006, **47**, 7367.

78 Y. Chauvin, L. Mussmann and H. Olivier, *Angew. Chem. Int. Ed.,* 1995, **15**, 2698.

79 Suarez, A. Z. Paulo, Dullius, E. L. Jeane, S. Einloft, De Souza, F. Roberto and J. Dupont, *Polyhedron,* 1996, **15**, 1217.

80 D. Xu, Z. Hu, W. Li, S. Luo and Z. Xu, *J. Mol. Catal. A: Chem.,* 2005, **235**, 137.

81 K. Anderson, P. Goodrich, C. Hardacre and D. Rooney, *Green Chem.,* 2003, **5**, 448.

82 T. Geldbach and P. Dyson, *J. Organomet. Chem.,* 2005, **690**, 3552.

83 M. Steffan, M. Lucas, A. Brandner, M. Wollny, N. Oldenburg and P. Claus, C*hem. Eng. Technol.,* 2007, **30**, 481.

84 C. Hardacre, E. Mullan, D. Rooney, J. Thompson and G. Yablonsky, *Chemical Engineering Science,* 2006, **61**, 6995.

85 M. Khodadadi-Moghaddam, A. Habibi-Yangjeh and M. Reza Gholami, *Appl. Catal. A.,* 2008, **341**, 58.

86 P. Dyson, D. Ellis and T. Welton, *Can. J. Chem,* 2001, **79**, 705.

87 Wolfson, I. Vankelecom and P. Jacobs, *Tetrahedron Lett.,* 2005, **46**, 2513.

88 A. M. Scurto and W. Leitner, *Chem. Commun.,* 2006, 3681.

89 T. Suarez, B. Fontal, M. Reyes, F. Bellandi, R. Contreras, J. Ortega, G. Leon, P. Cancines and B. Castillo, *React. Kinet. Catal. Lett.,* 2004, **82**, 325.

90 Z. Zhang, Y. Xie, W. Li, S. Hu, J. Song, T. Jiang and B. Han, *Angew. Chem. Int. Ed.,* 2008, **47**, 1127.

91 S. Bouquillon, T. Courant, D. Dean, N. Gathergood, S. Morrissey, B. Pegot, P. Scammells and R. Singer, *Aus. J. Chem.,* 2007, **60**, 843.

92 H. Blaser, C. Malan, B. Pugin, F. Spindler, H. Steiner and M. Studer, *Adv. Synth. Catal.,* 2003, 345.

93 R. Nyori, M. Kitamura and T. Ohkuma, *PNAS,* 2004, **101**, 5356.

94 F. Bautista, V. Caballero, J. Campelo, D. Luna, J. Marinas, A. Romero, I. Serrano and A. Llobet, *Topics in Catalysis,* 2006, **40**, 193.

95 Chan, S. Laneman and C. Day, *Inorg. Chim. Acta,* 1995, **228**, 159.

96 K. Wan and M. Davis, *Tetrahedron: Asymmetry,* 1993, **4**, 2461.

97 K. Boyle, B. Lipsky and C. Kalbery, *Tetrahedron Lett.,* 2006, **47**, 1311.

98 M. Schmitkamp, D. Chen, W. Leitner, J. Klankermayer and G. Francio, *Chem. Commun..,* 2007, 4012.

99 J. She, L. Ye, J. Zhu and Y. Yuan, *Catalysis Letters,* 2007, **116**.

100 T. Frater, L. Gubicza, A. Szollosy and J. Bakos, *Inorg. Chim. Acta,* 2006, **359**, 2756.

101 H. Wong, Y. H. See-Toh, F. C. Ferreira, R. Crook and A. G. Livingston, *Chem. Commun.,* 2006, 2063.

102 E. V. Starodubtseva, M. G. Vinogradov, V. A. Pavlov, L. S. Gorshkova and V. A. Ferapontov, *Russ. Chem. Bull. Int. Ed.,* 2004, **53**, 2172.

103 W. Xiong, Q. Lin, H. Ma, H. Zheng, H. Chen and X. Li, *Tetrahedron: Asymmetry,* 2005, **16**, 1959.

104 J. Wang, R. Qin, H. Fu, J. Chen, J. Feng, H. Chen and X. Li, *Tetrahederon: Asymmetry,* 2007, **18**, 847.

105 K. H. Lam, L. Xu, L. Feng, J. Ruan, Q. Fan and A. Chan, *Can. J. Chem.,* 2005, **83**, 903.

2 Synthesis, characterization and biological testing of a library of novel achiral imidazolium ILs

2.1 Introduction

An important factor in the design of biodegradable compounds is the presence of potential sites of enzymatic hydrolysis.[1-3] Due to their potential to be hydrolyzed, ester and ether/polyether side chains are incorporated into the achiral ILs in order to facilitate their breakdown in the environment. Lipophilic side chains present in previously synthesised ILs have been shown to be toxic. The presence of the ether oxygen atoms in the side chains of the novel ILs prepared are shown to reduce toxicity of the ILs. The bromide salts formed are converted to ILs of varying anions in order to modulate the properties of the novel ILs.

2.2 Synthesis of novel achiral ILs

The synthesis of these achiral ILs was carried out in two steps followed by anion exchange reactions (Figure 2.1).

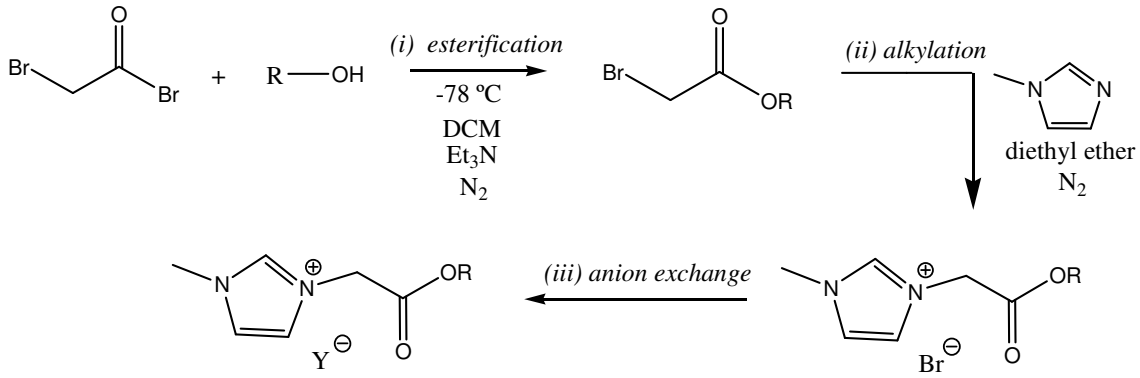
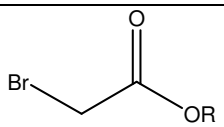


Figure 2.1 Three step synthesis of achiral ILs

2.2.1 Step 1: Esterification - Synthesis of α-bromoesters

The first step of the three-step synthesis of the achiral ILs involved the synthesis of the bromoesters, by the reaction of bromoacetyl bromide with alcohols of various side chain lengths and with differing numbers of oxygen atoms in their side chain (Table 2.1).



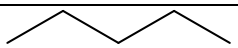
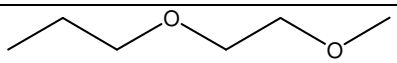
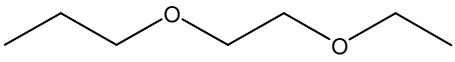
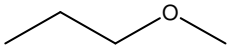
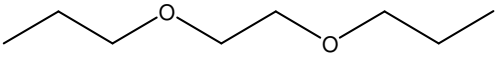
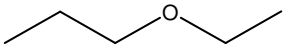
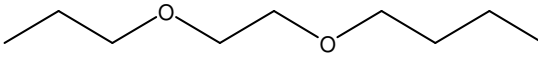
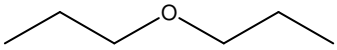
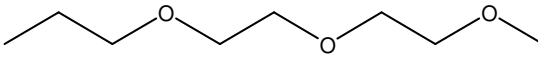
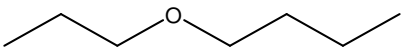
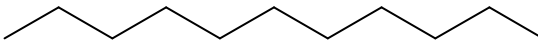
Alkylating agent (R)	Yield (%)	Alkylating agent (R)	Yield (%)
 **176a**	68	 **176g**	62
 **176b**	64	 **176h**	61
 **176c**	70	 **176i**	73
 **176d**	60	 **176j**	72
 **176e**	83	 **176k**	58
 **176f**	75	 **176l**	62

Table 2.1 α-bromoesters

The reaction yielded crude products which, although very darkly coloured, had high purity (> 97 %) by ^{1}H NMR analysis. As can be seen from a comparison of the spectrum of the pure and crude product respectively (Figure 2.2), little difference is evident between the two.

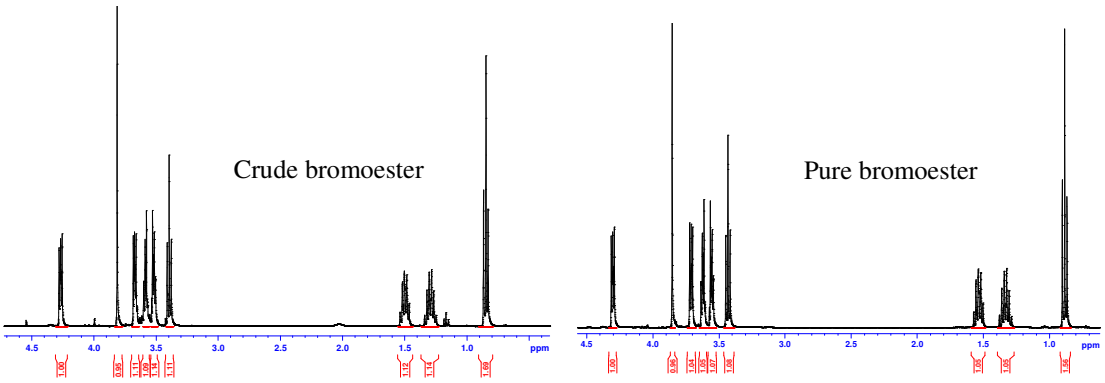
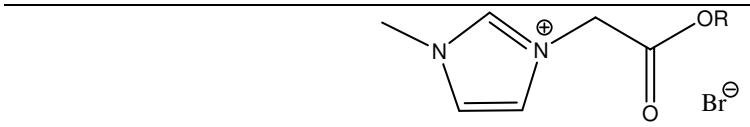


Figure 2.2 ^{1}H NMR of crude and pure bromoester (**176j**)

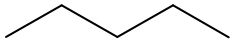
Following purification of the crude esters by vacuum distillation, pure products were obtained in good yields (58 – 83 %). The crude product (darkly coloured) was distilled to yield colourless to pale yellow pure products. This reaction was performed on a wide scale range, from 10 – 500 mmol, with no compromise in yield or purity. The reaction on the larger scales did however require increased reaction times, and the amount of bromoacetyl bromide used was increased to ensure reaction completion. Distillations of the crude products proved increasingly difficult as the side chain and the number of coordinating atoms in the side chain extended. This was presumably due to the increased molecular weight of the compound to be distilled, therefore possessing an increased boiling point. It is also evident from the lowest yield (58 %) being obtained for pure product for the bromoester with the longest chain and bearing oxygen atoms in this chain (**176k**).

2.2.2 Step 2: Alkylation - Synthesis of imidazolium bromide salts

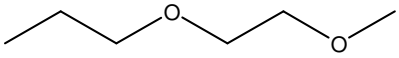
The alkylation of 1-methyl- and 1,2-dimethyl- imidazole with the esters and ethers of bromoacetyl bromide resulted in formation of the bromide salts (Table 2.2).



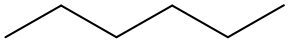
R



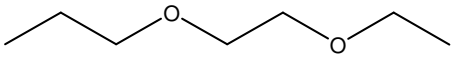
177a



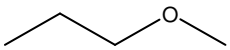
183a



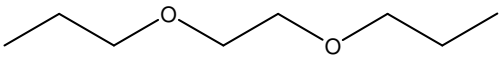
178a



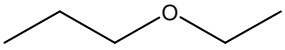
184a



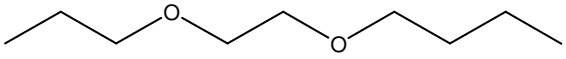
179a



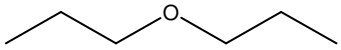
185a



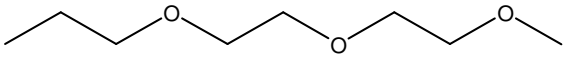
180a



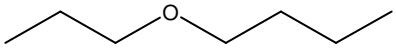
186a



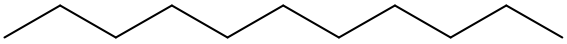
181a



187a



182a



188a

Table 2.2 Bromide salts

Excellent yields were obtained for this step of the reaction (82 – 98 %), apart from the synthesis of the longest chain bromide salt containing 3 ethereal oxygen atoms **187a** (55 %) and the C_{10} lipophilic chain bromide salt (51 %). Although most of the bromide salts obtained were solids at RT (**179-188** and **191**), their melting points were close to RT (Table 2.5). The initial duration of the reaction was 1 hour at – 15 ºC then warmed to RT for 3 hours. This time increased as the reactions were performed on larger scales. Diethyl ether was the solvent of choice for the reaction, with the desired imidazolium bromide salt precipitating out of solution. The number of washings of the product and the quantity of solvent used to wash them depended mostly on the viscosity of the IL. ILs which were solid at RT were usually clean after 3 - 4 washes for approximately 1 hour of stirring. On occasion, it took 2 days with continuous stirring to wash the viscous ILs in order to yield the bromide salts free from starting material contaminants. Time required for washing of the desired salts also took longer for the bromide salts based on the dimethyl imidazolium cation (Table 3). This was, in effect, due to the reduced solubility of the starting material, namely 1,2-dimethylimidazole, in the diethyl ether.

Due to this time taken and extensive washing required to obtain the pure bromide salt, THF was used in certain cases as washing solvent. The imidazole starting material, which was the main impurity, was more soluble in THF than diethyl ether, therefore facilitating more facile removal of this starting material from the bromide salt. In some cases, the IL was dissolved in DCM and washed with diethyl ether, thus the viscosity no longer posed the same problem. This method however did not appear to be efficient, and it was found that more starting material was removed if the IL was washed neat.

Three bromoesters of varying side chain lengths (**176b**, **176f** and **176g**) were used to synthesise the dimethylimidazolium bromide salts (Figure 2.3).

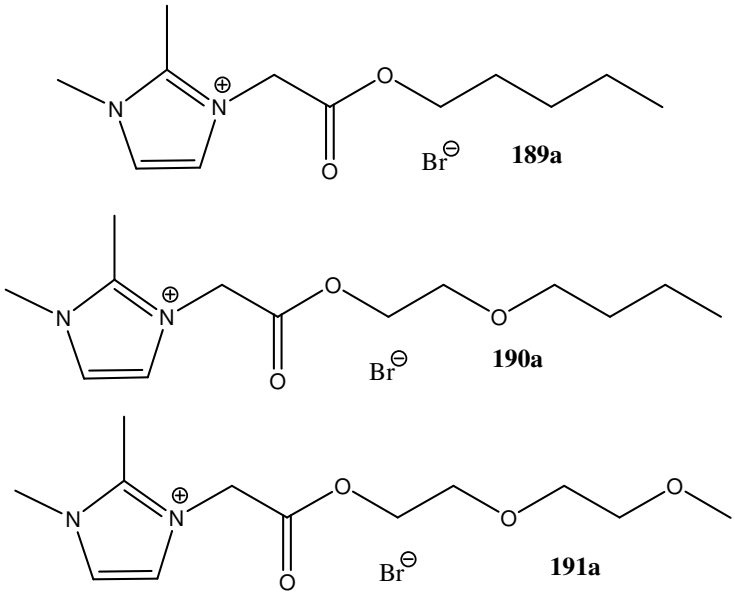


Figure 2.3 1,2-Dimethylimidazolium bromide salts

Significant differences in the ^{1}H NMR spectra between the methyl imidazolium and dimethylimidazolium derivatives were that the aromatic imidazolium peaks were split into a doublet in the case of the dimethylimidazolium derivatives, and triplets for the methylimidazolium derivatives (Figure 2.4).

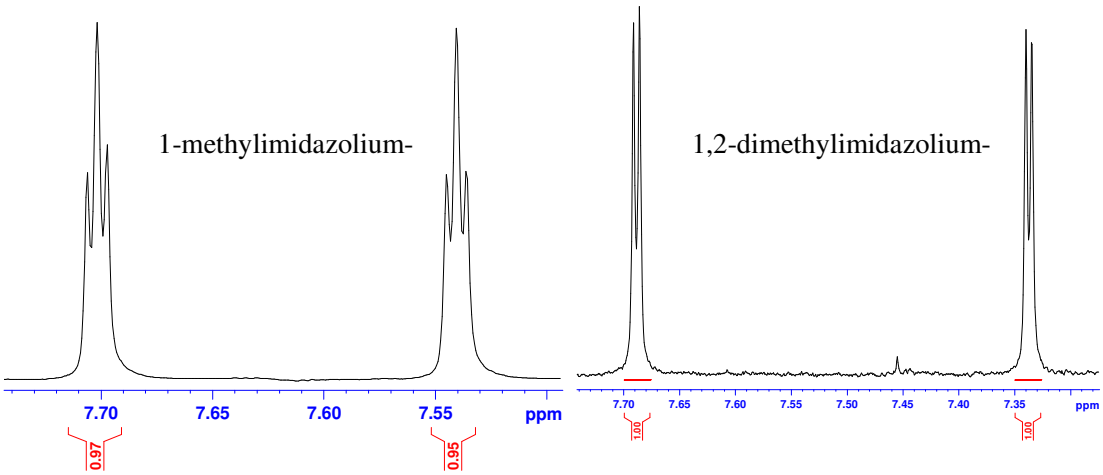


Figure 2.4 ^{1}H NMR triplet and doublet signals from imidazolium ILs

The splitting of the 1-methylimidazolium proton peaks into triplet signals is due to the mutual coupling of the three aromatic protons as can be seen from the COSY NMR spectrum (Figure 2.5).

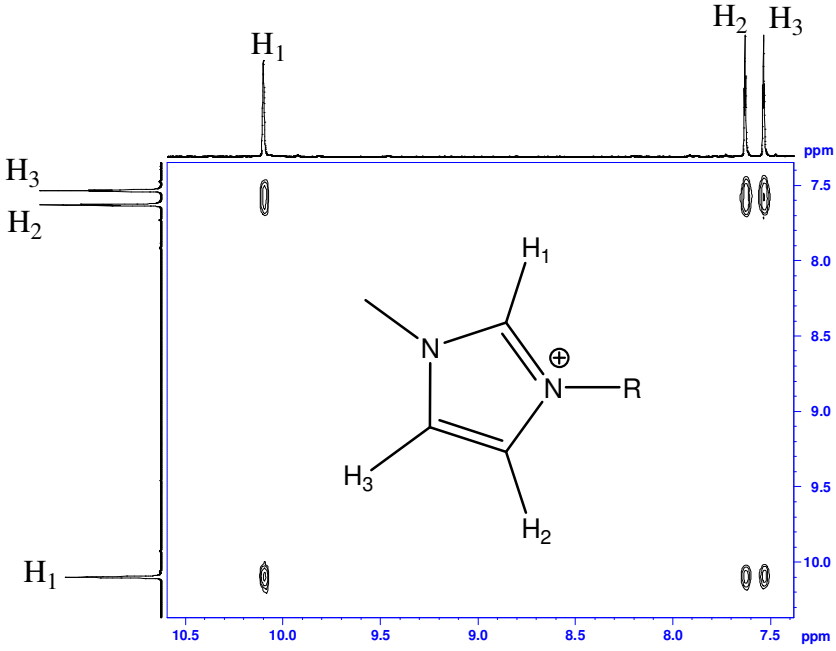


Figure 2.5 COSY ^{1}H-^{1}H NMR spectrum

Another difference between the 1-methyl and the 1,2-dimethyl derivatives of the imidazolium ILs is that an increase in melting point was observed for the dimethyl derivatives (Table 2.3).

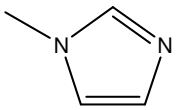
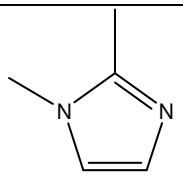
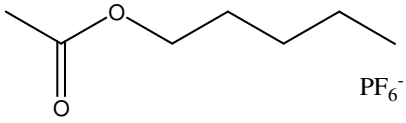
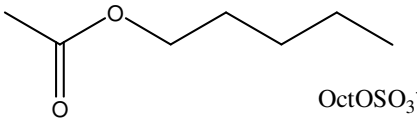
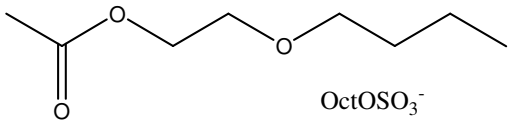
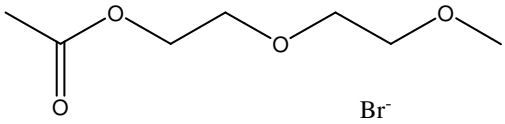
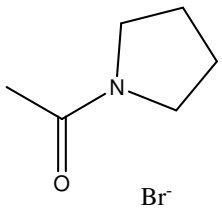
Side chain and anion	 mp (°C)	 mp (°C)
	Liquid at RT **178c**	40 – 42 **189c**
	Grease at RT **178f**	63 – 65 **189f**
	Liquid at RT **182f**	50 – 52 **190f**
	52 – 54 **183a**	74 – 75 **191a**
	109 – 111 **197a**	142 – 144 **198a**

Table 2.3 Melting point differences between 1-methylimidazolium and 1,2-dimethylimidazolium ILs

As can be seen from the differences in melting points between the different imidazolium derivatives (Table 2.3), the addition of a methyl group to the C_2 position leads to an increase in melting point of the IL. This is contrary to what would be expected as the removal and subsequent substitution of the C_2 acidic hydrogen should decrease the possibility of hydrogen bonding which, in theory, should hence decrease the melting point. This effect has been noted before and it seems that other interactions between the methyl group and the rest of the IL are more significant and thus increase the melting point.[4]

An interesting trend in melting point of bromide ILs is evident as the length of the side-chain and number of ethereal oxygens increases (Figure 2.6).

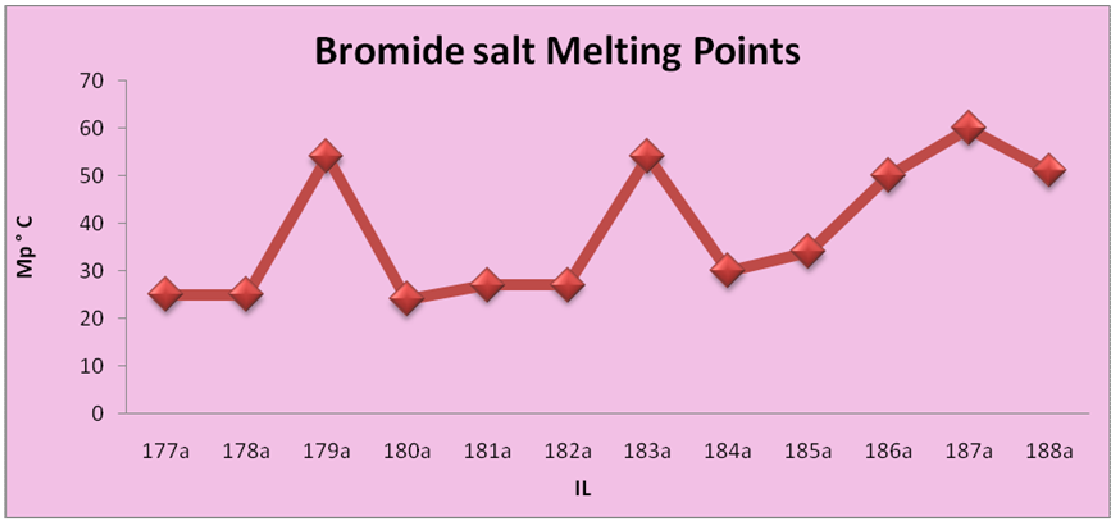


Figure 2.6 Bromide salt melting points (RT is taken to be 25 °C)

The highest melting points (peaks **179a**, **183a** and **187a**) are observed for the ILs terminating in a methyl group bonded directly to an ethereal oxygen atom. The reason for the elevated melting points is postulated to be due to the easier ability of the less flexible methyl terminus to fit into a crystal lattice in comparison with the increased flexibility of the ethyl/propyl/butyl termini.

The colours of the bromide salts varied from white and pale yellow to dark brown. In order to decolourise a selection of the bromide salts, activated charcoal was used. A method for purification of ILs was extracted and optimised for these novel ILs from Burrell *et al.*.[5] 2,3-Dimethyl-1-(pentoxycarbonylmethyl)imidazolium bromide (**189a**) was dissolved in distilled water containing charcoal and heated at 65 °C for 24 h. Following filtering of the solution from the charcoal and evaporation of the solvent, the initial bromide salt had changed colour from yellow to colourless (Figure 2.7).

Figure 2.7 189a Before and after purification

The same effect was also observed for **178a**, which was a similar colour to **189a**. **180a** was subjected to the same procedure in an attempt to remove the darker brown colour

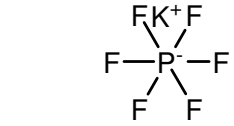
from the IL. After undergoing the same purification procedure, although a reduction in colour, from dark brown to yellow was observed (Figure 2.8), the colourless version of the IL could not be attained. Further heating for an extra 24 h resulted in degradation of the IL.

Figure 2.8 180a Before and after purification

Many of the bromide salts prepared were white powders. The viscous ILs can trap impurities more easily than the salts which precipitate as solids. The trace impurities are highly coloured, however, bromide salts which precipitate as white solids have high purity.

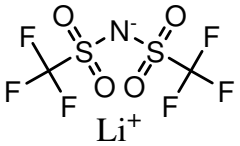
2.2.3 Step 3: Anion metathesis

Counter ion exchange reactions were carried out with sodium, postassium and lithium salts (potassium hexafluorophosphate, sodium tetrafluoroborate, sodium dicyanoamide, lithium trifluoromethanesulfonimide, sodium octyl sulfate) (Table 2.4).



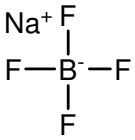
Potassium hexafluorophosphate

192



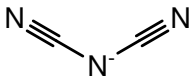
Lithium Trifluoromethanesulfonimide

193



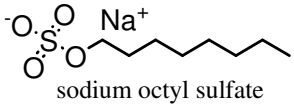
sodium tetrafluoroborate

194



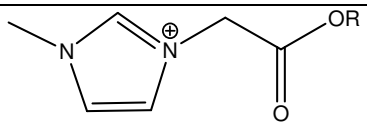
sodium dicyanoamide

195



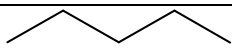
sodium octyl sulfate

196



[Br]/[PF_6]/[NTf_2]/[BF_4]/[$N(CN)_2$]/[$OctOSO_3$]$^{\ominus}$

a c d b e f



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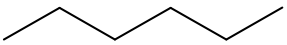

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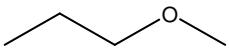

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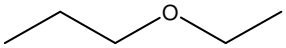

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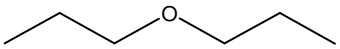

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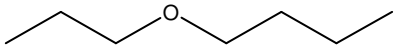

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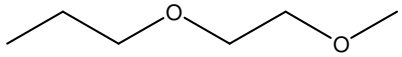

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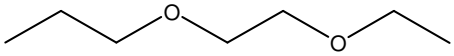

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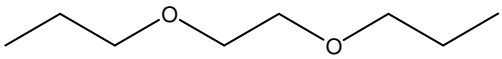

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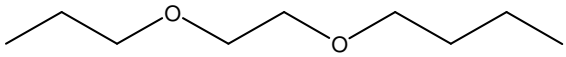

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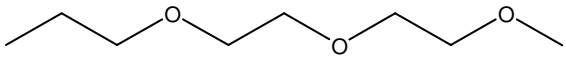

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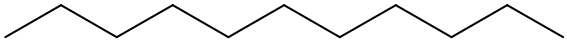


188

Table 2.4 ILs with different counter ions

Changing the counter ion of the bromide salts led to different properties observed for the ILs. Five different salts were used to observe this alteration in property. A general observation showed that changing the anion from bromide to [NTf_2] depressed the melting point of the IL. [NTf_2] and [PF_6] ILs were hydrophobic, and the [$OctOSO_3$] ILs were synthesised to increase biodegradability, as previously demonstrated by Gathergood *et al.*[6-9] All bromide salts converted to salts of different counter ions were predominantly liquids. The [$OctOSO_3$] salts were however greases at RT, with the

exception of two dimethylimidazolium derivatives (**189f** and **190f**), which displayed elevated melting points.

2.2.3.1 [NTf_2] ILs (d)

In order to synthesise the [NTf_2] salt, the bromide IL and the lithium salt were stirred vigorously at RT in water for times ranging from 4 – 18 hours. During this reaction time the hydrophobic IL precipitated out of solution and therefore could be washed with water to eliminate impurities. This reaction proceeded in good yield (68 – 95 %).

The hydrophobicity of these ILs meant that the decolourisation procedure previously described could not be carried out in the same manner. In an attempt to remove or reduce the colour of the preformed [NTf_2] salts, the IL was added to acetonitrile, and then stirred with charcoal and water at 65 °C for 24 h. The use of only acetonitrile as solvent showed no decolourisation of the product. However, the addition of water with the charcoal gave the result of **186d** changing colour from yellow/orange to practically colourless (Figure 2.9).

Figure 2.9 186d Before and after decolourisation

2.2.3.2 [PF_6] ILs (c)

The synthesis of the second hydrophobic IL, that of the [PF_6] counter ion, was initially carried out under similar conditions as the [NTf_2] salts; this however led to very poor yields. A change of solvent from water to acetone improved the yield slightly but still left room for improvement. Ultimately the [PF_6] ILs were synthesised by refluxing the two salts in acetone for four days with subsequent yields of > 90 % being obtained.

2.2.3.3 [BF_4] ILs (b)

The [BF_4] ILs were synthesised in the same manner as the [PF_6] ILs, for four days using acetone as a solvent. Excellent yields were obtained for this anion exchange reaction (>

92 % yield). Often however, the resulting alkali salts from the reactions were partially soluble in the IL, therefore making filtration challenging. If the acetone was however first evaporated and the product subsequently dissolved in dichloromethane, the unwanted salts precipitated thus facilitating their separation from the desired IL.

2.2.3.4 $[N(CN)_2]$ ILs (e)

The synthesis of the $[N(CN)_2]$ salts involved using acetonitrile as the solvent, but the reaction time of four days remained the same as the $[PF_6]$ and $[BF_4]$ ILs, again giving mostly good yields (51 – 99 %).

2.2.3.5 $[OctOSO_3]$ ILs (f)

With the $[OctOSO_3]$ ILs, the reaction conditions were changed dramatically. According to the literature,[10] the bromide salt and $NaOctOSO_3$ were stirred in water for 2 h at 60 ºC. The water was then slowly removed under vacuum. The precipitate was dissolved in DCM and washed with a small amount of distilled water. After evaporation of the solvent, the product was obtained in good yield, up to 98 %. The yield could however decrease rapidly if extreme caution was not taken during the water washing. That could be explained by the fact that the $[OctOSO_3]$ IL is soluble in water and is therefore easily removed upon washing with water. Once again it could be noted that only two of the $[OctOSO_3]$ ILs (**189f** and **190f**) are solid at room temperature but with melting points below 100 ºC. A major drawback of synthesising the $[OctOSO_3]$ ILs is the expense of the sodium salt. Due to this high cost, a method for its synthesis was extracted and developed from Ravi *et al.*.[11] 1-Octanol was dissolved in dichloromethane, followed by addition of chlorosulfonic acid. Subsequent neutralization of the mixture with $NaHCO_3$ and filtration with methanol permitted the synthesis of sodium octyl sulfate on a relatively large scale (20 mmol) in excellent yields (> 98 %).

A comparison of the yields and melting points of all novel achiral ILs can be viewed in Table 2.5.

IL cation % yield Melting point	[Br] a	[NTf_2] d	[BF_4] b	[PF_6] c	[$N(CN)_2$] e	[$OctOSO_3$] f
177	82	86	97	93	87	61
178	97	93	95	98	98	96
179	89 **53-55 °C**	91	95	96 **58 –60 °C**	80	95
180	93 **24-26 °C**	90	96	98	99	96
181	88 **25-27 °C**	68	97	97	91	85
182	89 **28- 30 °C**	84	96	95	51	93
183	97 **52- 54 °C**	91	94	91	94	82
184	92 **28-30°C**	87	96	96	99	93
185	98 **32- 34 °C**	82	93	91	85	98
186	94 **48- 50 °C**	86	92	79	98 **34 – 36 °C**	92
187	55 **59 – 61 °C**	93	94	57	75	84
188	51 **49-51 °C**	95	**-**	-	-	-
189	81	95	93	97 **40 -42 °C**	85	86 **63- 65 °C**
190	92	83	95	97	78	84 **50-52 °C**
190	88 **74-75 °C**	96	94	95	99	94

Table 2.5 Achiral ILs (yields and melting points)

2.2.4 Halide content of ILs

As residual halides remaining in the IL can pose problems for the ILs used in certain processes,[12, 13] the halide content of the ILs was investigated. The IL was dissolved in water/acetone and acidified with dilute nitric acid. Upon addition of silver nitrate, if a precipitate was observed (indicating the presence of residual halide) water washes were performed on the IL. Removal of excess halide from the hydrophobic ILs was therefore relatively straightforward. Hydrophilic ILs with [BF_4] and [$N(CN)_2$] counterions were a greater challenge to purify. In order to remove the residual halide, the IL in question was dissolved in dichloromethane and then washed with water. Numerous (>10) water washes were often required to completely remove the halide, thus the yield of the IL was often dramatically reduced due to its solubility in both the DCM and water layers.

2.2.5 NMR studies

All of the achiral salts were characterised by ^{1}H and ^{13}C NMR. For a series of ILs based on the same cation, with varying anion, the most distinguishing feature of the spectra is the shift in the signal for the acidic hydrogen of the imidazolium moiety. As can be seen from the spectra (Table 2.6), the chemical shift varies from 8.5 ppm in the case of the $[PF_6]$ counterion to 10.3 in the case determining the bromide salt. This facilitates a way of elucidation of the structure as well as which anion is present, even though the anion does not contain hydrogen atoms.

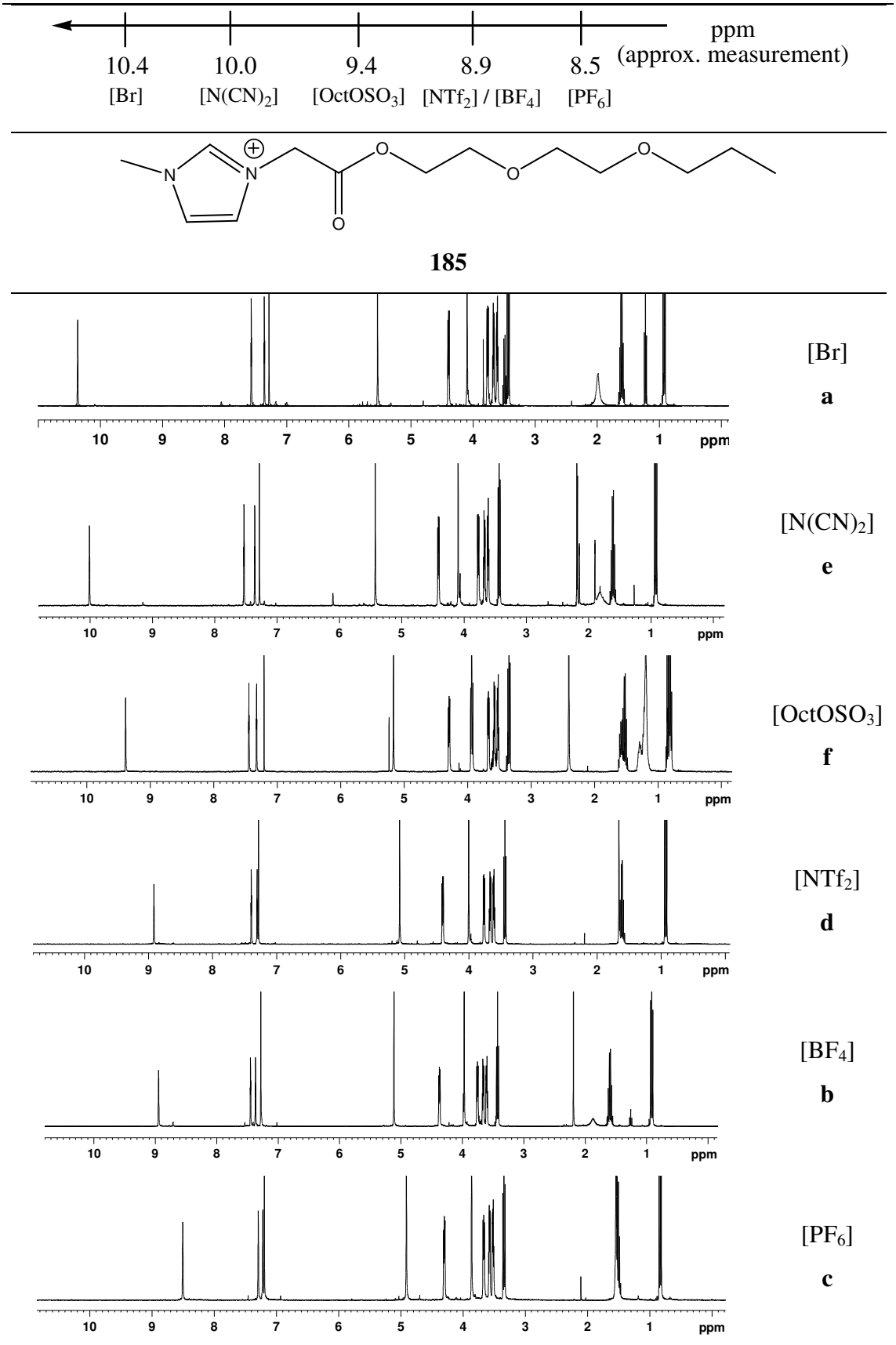


Table 2.6 ^{1}H NMR spectra for chemical shift comparison

This feature may also be used as a rough estimation of the varying degree of charge separation of the anion from the cation. The more deshielded the proton, the further downfield it appears, therefore indicating a more intense charge induced in the cation by the anion of the particular IL. From this estimation it can be seen that this pathway of elucidation of different anionic strengths imposed on their respective cations is relatively accurate. The bromide anion is seen have the greatest deshielding effect, as would indeed be estimated from the localised charge on this ion. As the anion becomes larger, and therefore the charge becomes more diffuse, the charge separation can be seen to decrease. The fluorinated anions in this case demonstrate the weakest deshielding effect on the cation. As the spectra for the same cations of the ILs of varying anions were similar, all ILs prepared were confirmed by mass spectrometry.

2.2.6 Amide ILs

The method for the preparation of the amide ILs was analogous to that for the ester derivatives except that the alcohol starting material was replaced by an amine (Table 2.7). The only difference noted was a slight possible change in method for the purification of the alkylating agent in the case of compound **202**. It was found that recrystallisation of the crude product from diethyl ether afforded the pure product, as an alternative to vacuum distillation. Excellent yields were obtained for the majority of the bromide and [$OctOSO_3$] amide derivatives; however elevated melting points were apparent in the case of the bromide salts, with all but one amide derivative being solid at RT (Table 2.8).

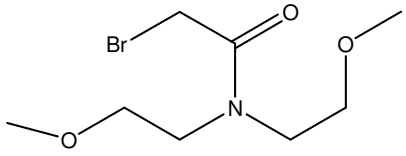
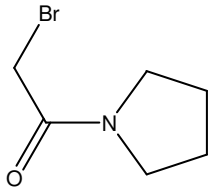
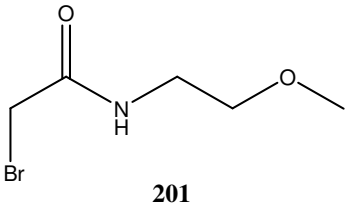
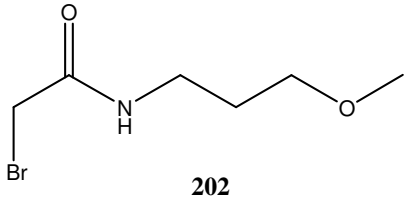
Amide bromoesters	Yield (%)
 **199**	49
 **200**	52
 **201**	17
 **202**	51

Table 2.7 Amide bromoester synthesis

The yield for the preparation of the amide derived alkylating agents is lower than obtained for the α-bromoesters. The yield ranged from 17-52 % in comparison with 68 - 83 % for the bromoesters. The amide functionality present also increased the melting point of these compounds as they are all in solid form as opposed to the bromoesters which were for the most part in liquid form. Due to the crystallinity of these materials, the procedure was changed slightly for the formation of the bromide salt. The dropwise addition was no longer used, and the solid material was dissolved in diethyl ether and added slowly to a solution of the imidazolium starting material in diethyl ether.

The yield for the synthesis of the amide derivatives of the bromide and [$OctOSO_3$] salts remains high (Table 2.8). A melting point above 100 °C, beyond the range for an IL, was observed for the pyrrolidine derivative. Changing the counter ion to [$OctOSO_3$], was shown to decrease this high melting point of a solid to a grease.

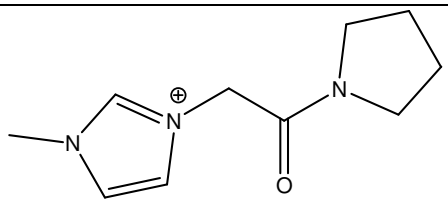
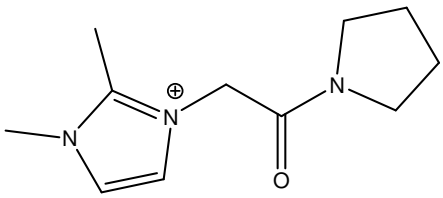
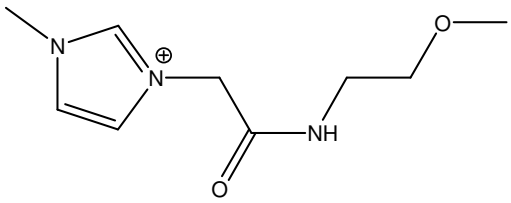
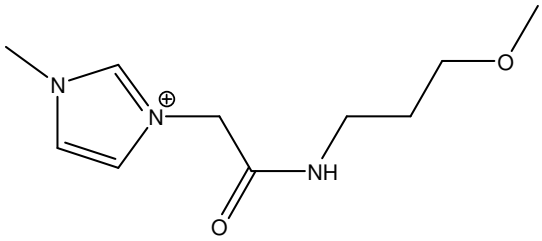
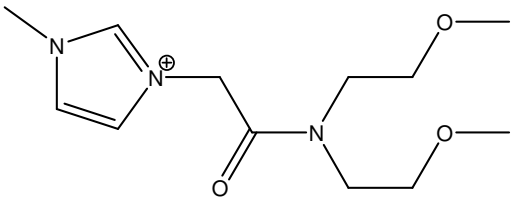
IL cation % yield **Melting point**	[Br] **a**	[$OctOSO_3$] **f**
 **197**	56 **109-111 ºC**	97
 **198**	82 **142-144 ºC**	98
 **203**	97	--
 **204**	91 **75-77 ºC**	--
 **205**	91 **68-70 ºC**	92

Table 2.8 Amide ILs (yields and melting points)

2.3 Toxicity and Biodegradation Studies

2.3.1 Toxicity studies

Toxicity studies have been performed on a wide range of the novel ILs synthesised to date. Seven strains of bacteria (Table 2.9) were used in the assessment of the level of activity against these strains on the ILs.

Gram negative bacteria	Gram positive bacteria
Pseudomonas aeruginosa	*Staphylococcus aureus*
Escherichia coli	*Enterococcus spp.*
Klebsiella spp.	*Bacillus subtilis*
Salmonella spp.	

Table 2.9 Bacteria used for toxicity testing

The minimum inhibitory concentrations were measured for those ILs which showed activity. A wide concentration range was tested (0 – 20000 μg/ml) to yield reliable results. It is evident from the resulting toxicity data that most of the novel ILs are non-toxic to these selected strains of bacteria. 3-Methyl-1-(decoxycarbonylmethyl) imidazolium bromide (**166l**) (Figure 2.10) was submitted for testing as a reference compound.

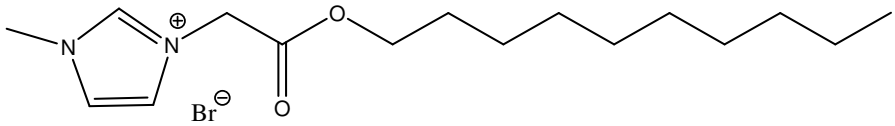


Figure 2.10 188a

Due to its long lipophilic side chain, lacking in coordinating atoms, it was presumed to be toxic. MIC values obtained from screening this compound against the seven strains of bacteria (Table 2.10) are low (1.9 – 125 μg/ml) thus signifying a high level of toxicity.

					E. coli						
Concentration (μg/ml)	1000	500	250	125	62.5	31.25	15.62	7.8	3.9	1.9	Control
Kill (%)	91	82	92	92	37	28	17	8.5	10	9	0
					Pseudomonas sp.						
Concentration (μg/ml)	1000	500	250	125	62.5	31.25	15.62	7.8	3.9	1.9	Control
Kill (%)	100	82	82	55.5	0	6	0	0	0	0	0
					Salmonella sp.						
Concentration (μg/ml)	1000	500	250	125	62.5	31.25	15.62	7.8	3.9	1.9	Control
Kill (%)	86	88	73.5	58	10	0	0	0	0	0	0
					Enterococcus sp.						
Concentration (μg/ml)	1000	500	250	125	62.5	31.25	15.62	7.8	3.9	1.9	Control
Kill (%)	96.4	84	83.4	49.5	48.7	18.7	23	6	6.5	6	0
					Klebsiella sp.						
Concentration (μg/ml)	1000	500	250	125	62.5	31.25	15.62	7.8	3.9	1.9	Control
Kill (%)	91.8	68.2	64	21	7	0	0	0	0	0	0
					S. aureus						
Concentration (μg/ml)	1000	500	250	125	62.5	31.25	15.62	7.8	3.9	1.9	Control
Kill (%)	100	96	93.8	80.7	90.3	86.4	88.2	90	66	27	0
					B. subtilis						
Concentration (μg/ml)	1000	500	250	125	62.5	31.25	15.62	7.8	3.9	1.9	Control
Kill (%)	100	83.2	81.5	80.2	0	0	0	0	0	0	0

Table 2.10 Toxicity of **188a** to bacteria strains

The same trend is evident in all bacteria used (Figure 2.11) with the exception of *S. aureus*. Bacterial growth is inhibited up to a concentration range of approximately 62 μg/mL. There is then a sharp increase in the percentage of bacteria killed. As can be

seen from the graph (Figure 2.11) after this sharp increase, the percentage of bacteria killed can be seen to plateau.

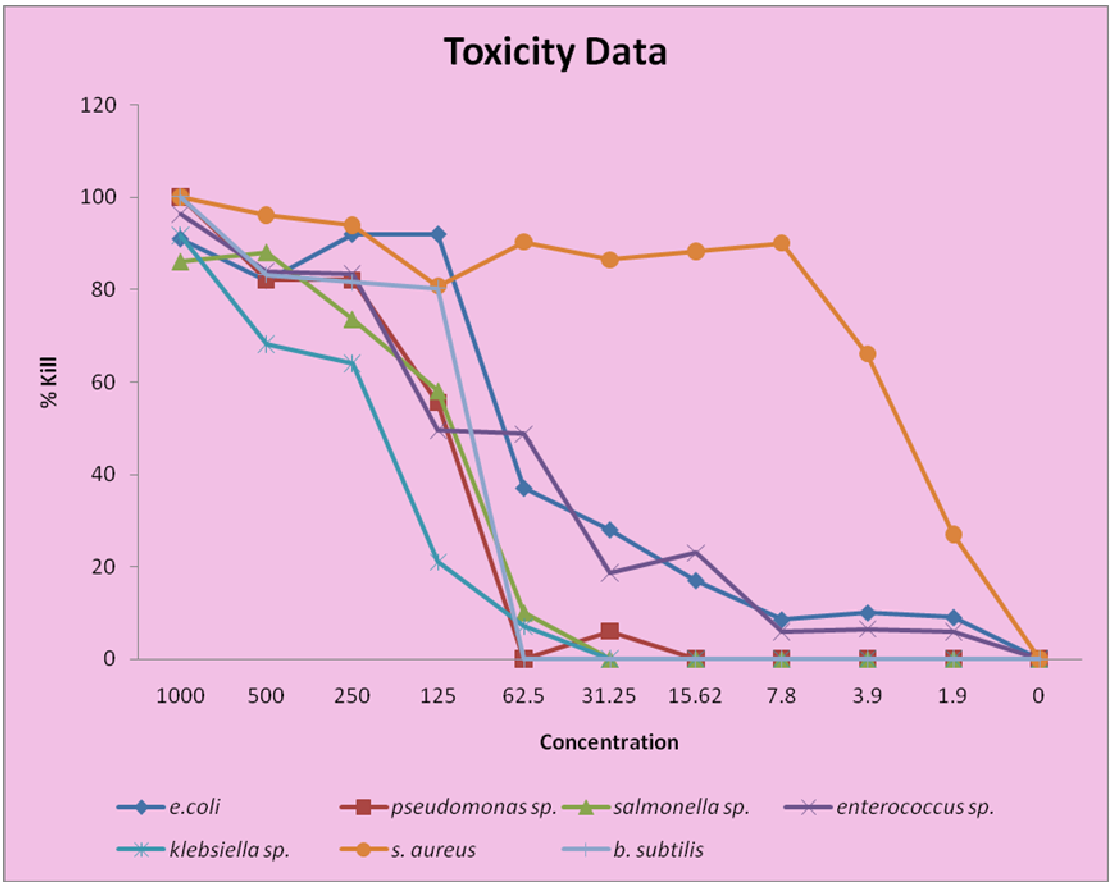


Figure 2.11 Toxicity profile of **188a**

Although some of the ILs tested demonstrate anti-microbial activity (Table 2.11), the MIC concentrations are still relatively high, thus indicating a lower level of toxicity than the readily toxic reference bromide salt.

IL Cation	MIC values (μg/ml)					
	[Br]	**[PF_6]**	**[$OctOSO_3$]**	**[NTf_2]**	**[BF_4]**	**[$N(CN)_2$]**
	a	**c**	**f**	**d**	**b**	**e**
177	>20000	>20000	**5000**	**10000**	>20000	**5000**
178	>20000	>20000	>20000	**10000**	**10000**	**10000**
179	>20000	>20000	>20000	**10000**	>20000	>20000
180	>20000	>20000	>20000	>20000	>20000	>20000
181	>20000	>20000	>20000	**10000**	>20000	>20000
182	>20000	>20000	>20000	>20000	>20000	>20000
183	>20000	**2500**	>20000	**10000**	>20000	>20000
184	>20000	>20000	**10000**	>20000	>20000	>20000
185	>20000	>20000	>20000	>20000	>20000	>20000
186	>20000	>20000	**10000**	>20000	>20000	>20000
189	>20000	>20000	>20000	>20000	**5000**	>20000
190	>20000	>20000	**10000**	>20000	>20000	>20000
191	>20000	>20000	**10000**	>20000	>20000	>20000

Table 2.11 Toxicity of ILs to seven bacteria strains

The evidence obtained from this study demonstrates that the anion has a significant influence on toxicity. Analysis of this table of toxicity data demonstrates the bromide salts to be non-toxic. ILs with [$OctOSO_3$] and [NTf_2] as anion are the most toxic, followed by [BF_4] and [$N(CN)_2$], with [PF_6] showing similar non-toxicity to the bromide salts; only one [PF_6] IL (**183c**) shows toxicity.

Also evident, is that regardless of anion influence the short butyl (**177d**, **177e**, **177f**) and pentyl (**178b**, **178d**, **178e**) lipophilic side chain containing ILs display toxic effects for three ILs, rendering them the most toxic cations tested thus far. The absence of acidic hydrogen on the C_2 position of the imidazolium moiety is shown to alter the toxicity of some cations in comparison with 1-methylimidazolium derivatives. In the case of the pentyl derivative (**178** and **189**), the 1-methylimidazolium ILs are more toxic than the 1,2-dimethylimidazolium derivatives. Although the dimethylimidazolium derivative of this cation is shown to be toxic in conjunction with the [BF_4] salt (**189b**), this [BF_4] salt (**178b**), as well as the [NTf_2] (**178d**) and [$N(CN)_2$] (**178e**) salts are toxic in the case of the 1-methylimidazolium derivative. The opposite effect can be noted for the

butoxyethoxy side chain derivative (cations **182** and **188**). The 1-methylimidazolium salts are non toxic, while the [$OctOSO_3$] salt of the dimethylimidazolium derivative (**190f**) is toxic at a concentration of 1000 μg/ml. The methoxyethoxyethoxy ILs are more toxic to these bacteria with the 1-methylimidazolium cation (**183**). At a low concentration of 2500 μg/ml, the [PF_6] IL of this derivative (**183c**) is toxic, as well as the [NTf_2] IL (**183d**) which is toxic at a higher concentration (10000 μg/ml). It is only with the [$OctOSO_3$] salt of the dimethylimidazolium derivative of this IL that toxicity is observed (**191f**).

2.3.2 Biodegradation studies

To evaluate the biodegradability of the [$OctOSO_3$] ILs, the ''CO_2 Headspace'' test (ISO 14593)[14] was applied (Table 2.12). This method allows the evaluation of the ultimate aerobic biodegradability of an organic compound in aqueous medium at a given concentration of micro-organisms by analysis of inorganic carbon. The test IL, as the sole source of carbon and energy, was added at a concentration of 40 mg L^{-1} to a mineral salt medium. These solutions were inoculated with activated sludge collected from an activated sludge treatment plant, washed and aerated prior to use and incubated in sealed vessels with a headspace of air. Biodegradation (mineralization to carbon dioxide) was determined by measuring the net increase in total organic carbon (TOC) levels over time.

IL no.	Days					IL no.	Days				
	0	**7**	**15**	**21**	**28**		**0**	**7**	**15**	**21**	**28**
SDS	0	81	85	90	92	**184f**	0	51	56	56	56
177f	0	45	54	56	59	**185f**	0	42	62	63	66
178f	0	52	59	60	64	**186f**	0	56	61	64	65
179f	0	54	59	59	59	**190f**	0	53	54	62	65
180f	0	54	57	59	57	**191f**	0	50	52	54	55
181f	0	51	58	61	65	**197f**	0	27	32	36	36
182f	0	53	59	60	61	**198f**	0	26	30	35	35
183f	0	32	56	58	58	**205f**	0	26	30	29	29

Table 2.12 CO_2-Headspace Test Results for [$OctOSO_3$] ILs

It can be seen that the ILs containing the ester linkage, regardless of side chain, display a similar pattern of biodegradation, all coming close to or surpassing the pass level within 28 days (55-66 %) (Figure 2.12).

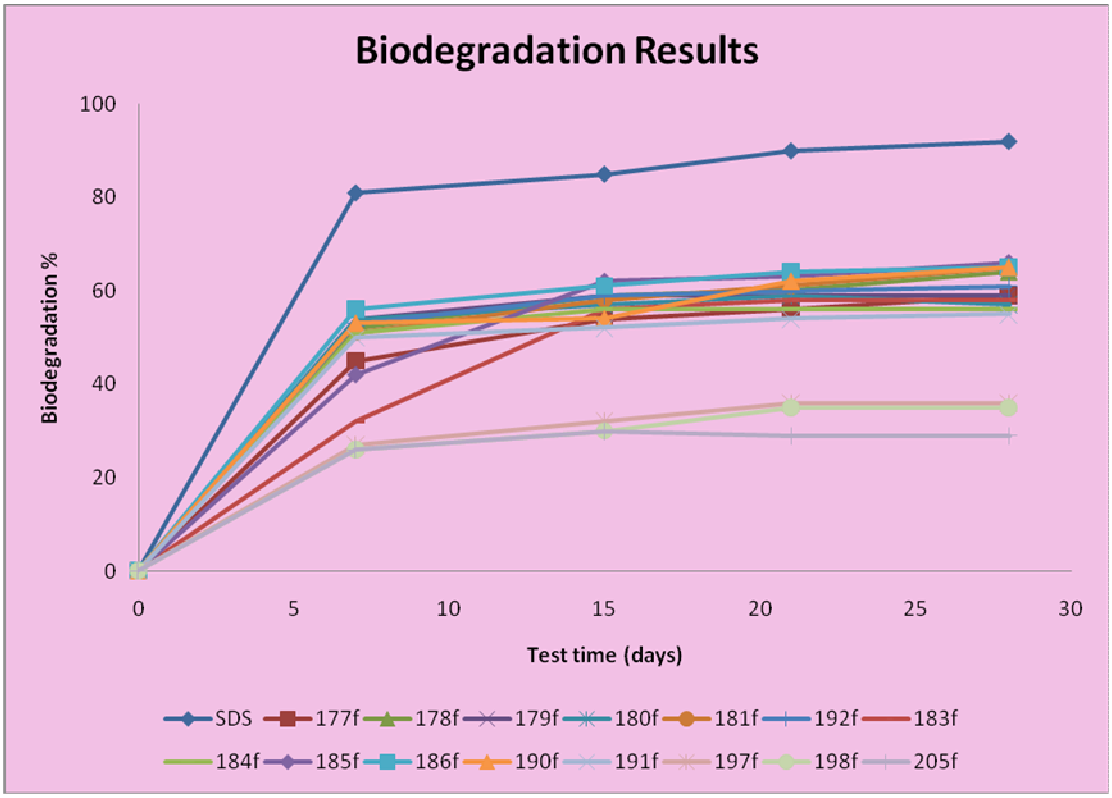


Figure 2.12 IL biodegradation results

The importance of having an ester linkage present in the ILs is highlighted by the fact that when this functionality is replaced by an amide linker, the biodegradation is seen to decrease dramatically. After 28 days, the percentage biodegradation obtained for the amide [$OctOSO_3$] ILs ranged from a mere 29 - 36%. It is also interesting to note the effect a single methylene group can have on the biodegradation of a compound. Compound **184f** displayed a satisfactory biodegradation result of 56 %, while the incorporation of a methylene group in compound **185f** raised this compound above the pass level (66 %). The same effect is evident again, albeit to a lesser extent with compounds **180f** and **181f** and lipophilic side chain ILs **177f** and **178f**. The presence of an extra oxygen atom in the side chain can be seen to negatively interfere with the biodegradation in certain cases. The only difference between compounds **190f** and **191f** is the last ethereal oxygen atom on the side chain of **191f** is replaced in **190f** by a methylene group. There is a 10 % decrease in biodegradation however with the presence

of this supplementary oxygen. A similar effect may be observed comparing compounds **182f** and **183f**, although the difference in percentage biodegradation is less dramatic.

2.4 Structural study of selected bromide ILs

Although, most uses of ILs are performed while in the liquid state, valuable information may be gathered about local interactions in the IL from the solid state crystal structure. From a selection of bromide salts that were solid at RT, an attempt was made to grow crystals for X-ray crystallographic analysis. Many different methods and solvent systems were attempted for a variety of the solid salts. The two compounds that successfully formed crystals suitable for measurement were **186a** and **191a**. **186a** was grown from a hot saturated solution of the product in an NMR tube containing acetonitrile. The hot saturated solution was allowed to cool and was left for several weeks, until the acetonitrile had evaporated, after which identifiable crystals could be removed from the tube. Crystals were grown from **191a** using a binary solvent system (dichloromethane and hexane) by a vapour diffusion method. The IL was dissolved in dichloromethane in a small plastic vial. This vial was then placed into a bigger plastic vial containing hexane. The system was sealed and allowed to stand for one month before crystals were evident. Both crystals were colourless and some relevant crystallographic information on them is summarised in sections **2.4.1** and **2.4.2**.

2.4.1 191a

191a crystallises in the monoclinic space group $P2_1/c$ with one ionic pair per asymmetric unit (Figure 2.13).

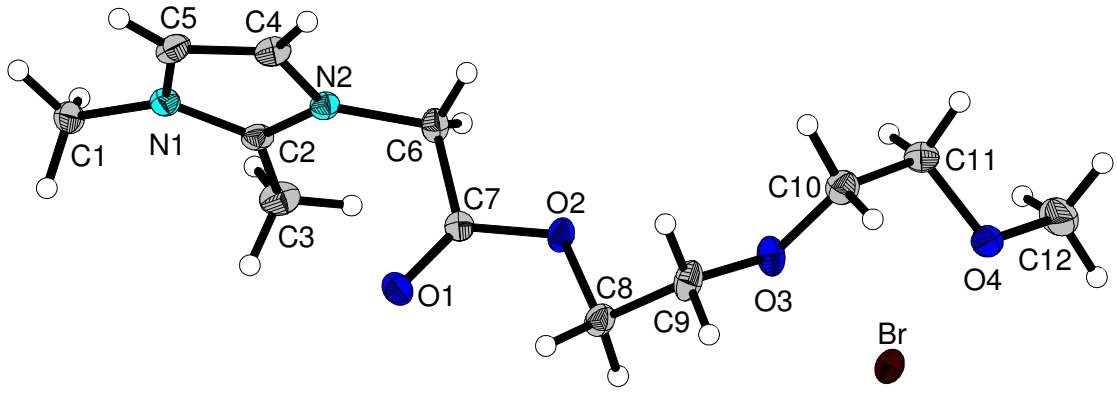


Figure 2.13 191a thermal ellipsoids are drawn on the 50 % probability level

The electrons of the planar imidazolium ring are delocalised. This is evident from the shortened C-N and C-C bonds comprising the aromatic ring in comparison with the C-N

and C-C bonds for the rest of the structure. Bond lengths for N1-C2, N2-C2, N1-C5 and N2-C4 are ≤ 1.380 Å. These values are less than the bond length observed for the same nitrogen atoms bonded to atoms adjacent to, but not directly involved in the delocalised bonding (C1-N1 = 1.469 Å, N2-C6 = 1.454 Å). The same phenomenon can be seen with the bond length value for the aromatic C4-C5 bond (1.340 Å) being less than the non-aromatic C2-C3 bond (1.476 Å). The lengths of the bonds in the imidazolium ring are not evenly distributed, with the bonds directly bonded to the C2 bearing the second methyl group being shorter (N1-C2 = 1.334 Å and C2-N2 = 1.343 Å) than the other two remaining nitrogen containing aromatic bonds (N1-C5 = 1.378 Å and N2-C4 = 1.380 Å). The ethereal side chain of the IL is not planar with the imidazolium ring, the first deviation occurring between C2-N2 and C6-C7 (C2-N2-C6-C7 = -86.6 °). The bond length for C7-O1 is shorter (1.198 Å) than that of C7-O2 (1.335 Å), resulting from the stronger double bond holding atoms C7 and O1 together. The evidence of partial double bond character can be seen from the bond length of C7-O2, which, although greater than that of the carbonyl group, is less than the bond lengths between carbon and ethereal oxygen atoms in the side chain, which range from 1.413 – 1.425 Å. The greatest C-O bond length is evident between O2 and C8. The mesomeric effect of the ester moiety resulting in less net negative charge on the O2 atom is evident, thus leading to a weaker bond and therefore a longer bond length in comparison to the bond lengths observed for the ethereal oxygens to adjacent methylene groups.

2.4.2 186a

186a (Figure 2.14) also crystallises in the monoclinic space group $P2_1/c$, however it has two structurally similar but crystallographically distinct ion pairs (A and B) per asymmetric unit (Figure 2.15).

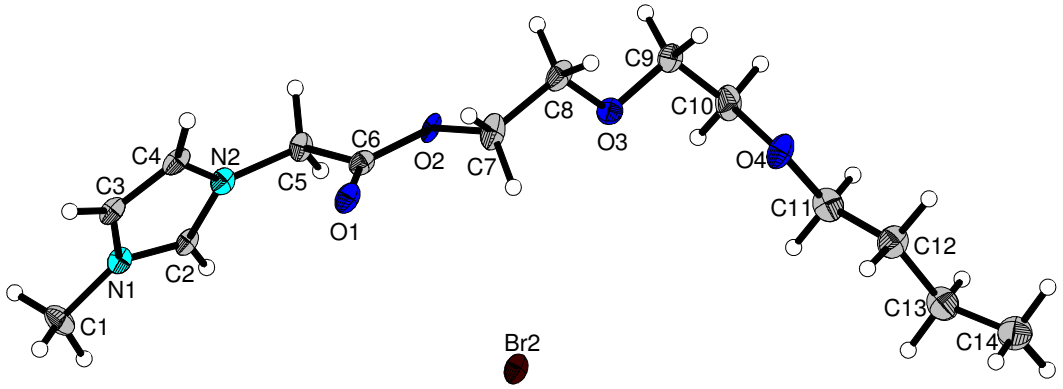


Figure 2.14 186a thermal ellipsoids are drawn on the 50% probability level

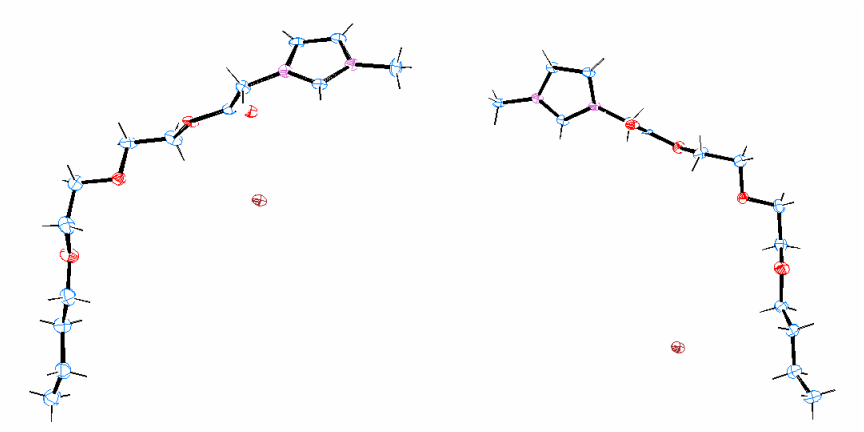


Figure 2.15 Ortep representation of molecule A and molecule B

The bond lengths for both molecule A and molecule B were approximately equal, and no notable differences were observed. The greatest differences noted between the two molecules however were the torsion angles. As there were many differences in these values, differences of ≥ 4 ° were noted. The torsion angle between the imidazolium atoms (C2 and N2) and the methylene and carbonyl carbons (C5 and C6) is more pronounced in molecule A (-114.1 °) than in molecule B (-110.6 °). The case is the same for the C4 and N2 plane where, this time molecule B displays the greatest torsion angle (65.7 °) as opposed to molecule A (60.4 °). By far the greatest deviation in terms of torsion angle may be noted around the ester moieties of both molecules. It is between the N2-C5 plane and the C6-O2 plane that molecules A and B can be seen to adopt almost equal but opposite conformations (-177.8 ° and 179.1 ° respectively). The carbonyl group of molecule A is more in plane (-3.0 °) with the other ester oxygen and following methylene group (O2-C7) than molecule B (-6.7 °). A significant difference can also be seen between both molecules for the C9-C10/O4-C11 planes (170.6 and 176.0 ° for molecules A and B respectively).

It can be seen by comparison between **186a** and **191a** that not many differences are observed between these molecules in terms of bond angles or length due to the presence of a methyl group at the C2 position of **191a**. The same phenomenon can be seen in **186a** as was found in **191a** in terms of the differing bond lengths in the imidazolium ring, and the nitrogens being more closely bound to the intermittent carbon atom than to the two carbon atoms joined by a double bond. The same expected trend in bond lengths between carbon atoms and ester or ethereal oxygens can also be seen for both **186a** and **191a**.

2.5 Conclusion

The synthesis and structural characterization of a library of novel achiral ILs has been carried out. 12 bromoesters were prepared. 15 bromide salts, 15 [NTf_2], 14 [$N(CN)_2$], 14 [BF_4], 14 [PF_6] and 14 [$OctOSO_3$] were successfully synthesised and characterised. Concerning the amide derivatives, 4 bromoesters, 5 bromide salts and 3 [$OctOSO_3$] ILs were prepared. It was shown that these achiral ILs containing polyether and alkyl side chains of varying lengths could indeed be classified under the term ionic liquid and therefore be potentially used as alternatives to harmful organic solvents. It has also been established that altering the counter ion leads to varying properties, such as the viscosity or an increase or depression of melting point. The toxicity data obtained shows that the addition of oxygen atoms in the side chains of the ILs is shown to decrease toxicity. It is thought that this is due to the oxygen atoms decrease the lipophilicity of the side chain, thus making it more difficult to penetrate the cell membrane. The biodegradability data gathered confirms that the inclusion of an ester linkage in the ionic liquid assists in the biodegradation of the compounds. The ester and polyether functionality in these novel ILs show that a range of ILs can be synthesised which lie within the definition of ILs.

2.6 Bibliography

1 P. H. Howard, R. S. Boethling, W. Stiteler, W. Meylan and J. Beauman, *Sci. Total Environ.,* 1991, 109.

2 R. S. Boethling, *Cationic Surfactants, Surfactant Science Series,* 1994, **53**, 95.

3 R. S. Boethling, *Designing Safer Chemicals, ACS Symp. Ser.,* 1996, 156.

4 P. Wasserscheid and T. Welton, *Ionic Liquids in Sythesis*, Wiley-VCH, 2008.

5 Burrell, R. Del Sesto, S. Baker, T. McCleskey and G. Baker, *Green Chem.,* 2007, **9**, 449.

6 N. Gathergood and P. J. Scammells, *Aust. J. Chem.,* 2002, **55**, 557.

7 N. Gathergood, M. T. Garcia and P. J. Scammells, *Green Chem.,* 2004, **6**, 166.

8 M. T. Garcia, N. Gathergood and P. J. Scammells, *Green Chem.,* 2004, **7**, 9.

9 N. Gathergood, P. Scammells and T. Garcia, *Green Chem.,* 2006, **8**, 156.

10 P. Wasserscheid, R. van Hal and A. Bosmann, *Green Chem.,* 2002, **4**, 400.

11 S. Ravi, K. M. Mathew, Unny, V. K. P. and N. Sivaprasad, *J. Label. Compd. Radiopharm.,* 2005, **48**, 1055.

12 Y. Chauvin, L. Mussmann and H. Olivier, *Angew. Chem. Int. Ed.,* 1995, **15**, 2698.

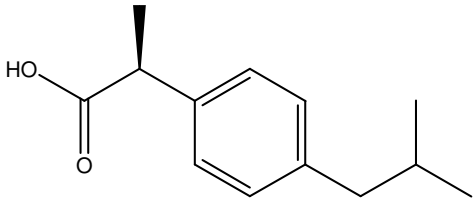
13 M. Klingshirn, G. Broker, J. Holbrey, K. Shaughnessy and R. Rogers, *Chem. Commun.,* 2002, , 1394.

14 ISO 14593: *Water quality, Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium. Method by analysis of inorganic carbon in sealed vessels* (CO_2 headspace test), 1999.

3 Synthesis, characterisation and biological testing of a library of novel imidazolium CILs

3.1 Introduction

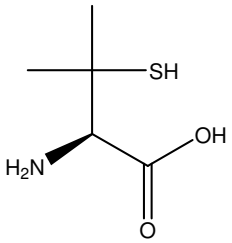
Preparation of enantiomerically pure compounds is of utmost importance, with the formation of one of a pair of enantiomers being desirable. This has been demonstrated by the tragic effects that can be caused by the presence of the opposite enantiomer of a drug in an otherwise successful drug, a prominent example being that of the thalidomide tragedy.[1] Another example, albeit of less detrimental consequences is the NSAID ibuprofen (**206**) (Figure 3.1), which is sold over the counter in many countries.



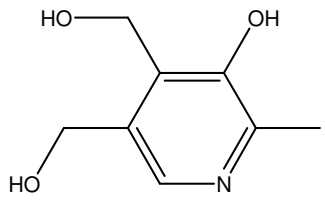
ibuprofen
206

Figure 3.1 (*S*) Ibuprofen (**206**)

The (*S*) enantiomer of this 2-arylpropionic acid derivative is three times more potent than the (*R*) enantiomer, therefore the requirement for asymmetric synthesis of the desirable enantiomer is of importance.[2] Penicillamine (**207**), used to treat the autoimmune disease, rheumatoid arthritis, is sold in the (*S*) form because the (*R*) form inhibits the action of pyridoxine (**208**) (also known as vitamin B6) and thus has led to severe adverse effects in patients (Figure 3.2).[3]



Penicillamine
207



pyridoxine
208

Figure 3.2 Penicillamine (**207**) and pyridoxine (**208**)

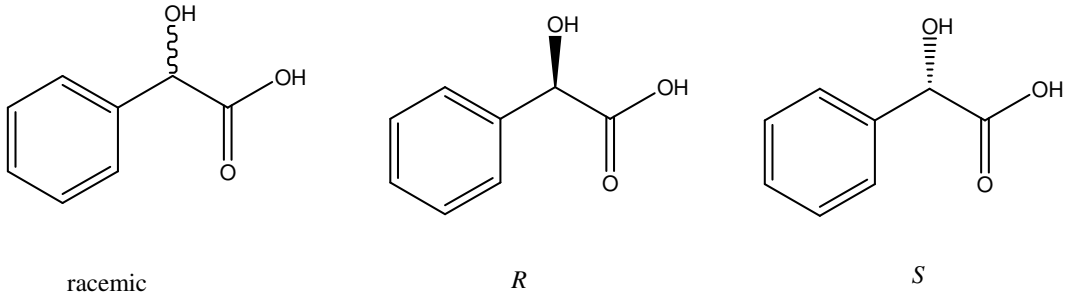
The use of enantiomerically pure precursors with the desired absolute configuration already present derived directly from the chiral pool[4] is attractive and widely used, however there is a limit to naturally occurring products available in this form. The use

of enantiomeric separation techniques, such as chiral separation by chromatography[5] can also be used to extract the desired enantiomer following a symmetric synthesis of the desired product. This can however prove to be costly, and of negative impact to the environment, with large quantities of solvent often being needed to perform these procedures. Traditional asymmetric synthesis provides a practical method for achieving enantiomeric purity. Enantioselective synthesis may be carried out using a chiral starting material. This however entails that at least a stoichiometric amount of the starting material would be essential, thus possibly rendering this method expensive. The use of chiral catalysts[6] may overcome this problem as only a sub-stoichiometric amount would be required to induce chirality. One technique which is constantly evolving is chiral induction arising from the use of a chiral solvent.[7-9] A library of novel chiral ILs containing an ester linkage is prepared from mandelic and lactic acid with a view to be used as chiral induction solvents in asymmetric synthesis.

3.2 Synthesis of novel CILs

Mandelic (**53**) and lactic acid (**52**) are readily commercially available in their racemic and enantiomerically pure forms (Figure 3.3), thus making these compounds ideal for the introduction of chirality into the novel ILs. Mandelic acid was chosen to integrate into the ILs due to its chiral centre being surrounded by the hydroxyl and phenyl group. This was thought to have potential for chirality induction. As the phenyl group was presumed to increase the melting points of the formed ILs, lactic acid was used also due to the absence of this group.

Mandelic acid **53**



Lactic acid **52**

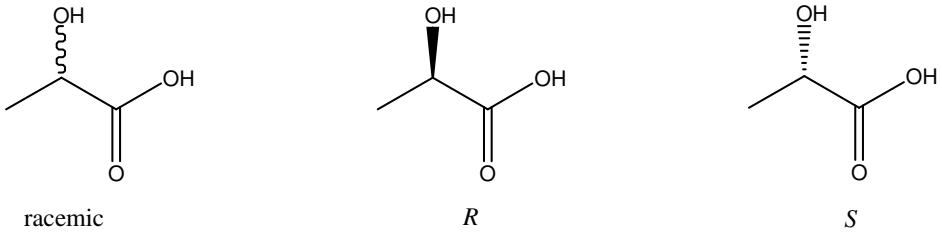


Figure 3.3 Mandelic and Lactic acid

These chiral carboxylic acids can easily be modified by esterification, thus adding potential to modulate their properties. The ester linkage evident in our achiral ILs may be maintained by reaction of the formed esters with bromoacetyl bromide. The synthetic steps followed to obtain these chiral ILs are essentially the same as carried out with the achiral derivatives (Figure 3.4).

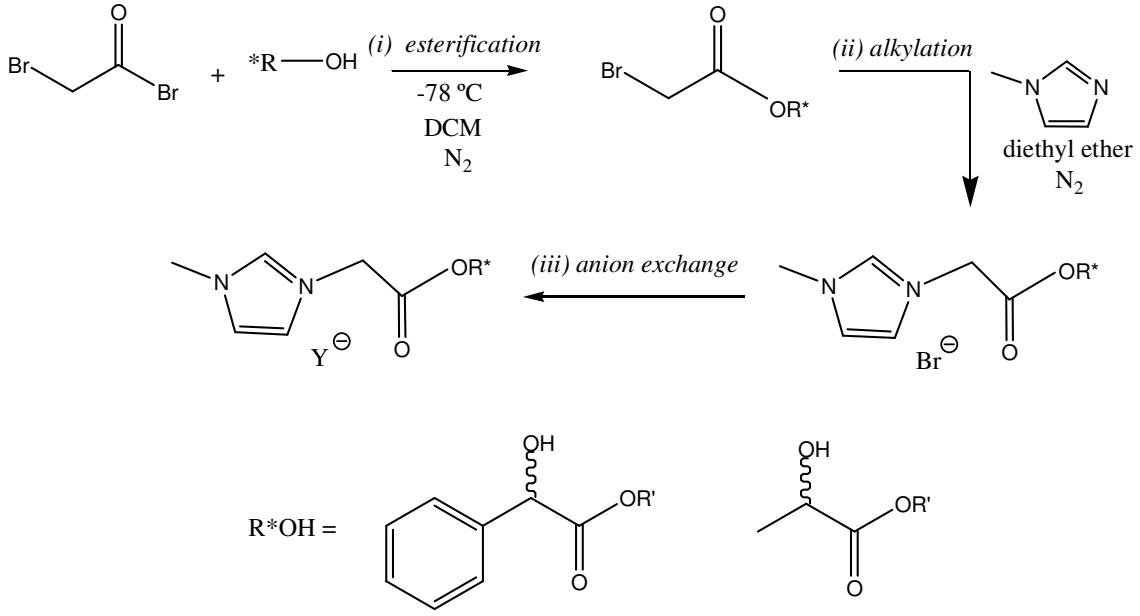
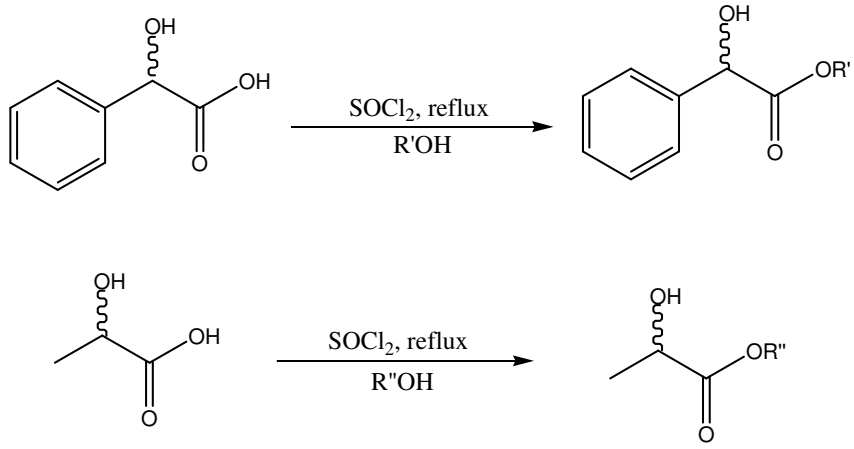


Figure 3.4 Synthesis of chiral ILs

3.2.1 Esterification of mandelic and lactic acid

An extra step was introduced at the beginning of the synthesis in order to synthesise the chiral ester with varying side chains (R) (Figure 3.5). This reaction, adapted from Moormann *et al.*[10] is carried out under reflux conditions, using no solvent, a sub-stoichiometric amount of thionyl chloride, and the alcohol in excess. This reaction was monitored by TLC, and it was found after a few trial reactions that six hours was sufficient time for reaction completion.



R'OH = ethanol, butanol, pentanol, ethoxyethanol
R"OH = methanol, ethanol, propanol, butanol, pentanol, ethoxyethanol

Figure 3.5 Synthesis of chiral starting materials

This reaction proceeded in excellent yields for both mandelate (**209**) (82 – 100 %) and lactate (**210**) (74 – 97 %) derivatives (Table 3.1).

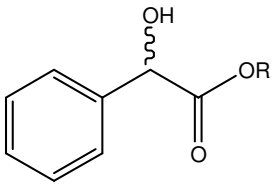
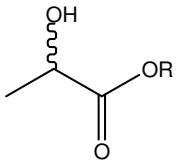
Mandelate derivative **209**				Lactate derivative **210**		
						
R:	***R***	***S***	***RS***	**R:**	***R***	***RS***
CH_3	85*** m**	82*** n**	99 **o**	CH_3	79 **a**	84* **b**
C_2H_5	98 **a**	84 **b**	100 **c**	C_2H_5	77* **c**	97 **d**
	-	-	-	C_3H_7	79* **e**	74* **f**
C_4H_9	100 **d**	98 **e**	100 **f**	C_4H_9	78* **g**	80* **h**
C_5H_{11}	95 **g**	97 **h**	98 **i**	C_5H_{11}	88* **i**	75* **j**
$C_2H_4OC_2H_5$	84 **j**	85 **k**	99 **l**	$C_2H_4OC_2H_5$	79* **k**	92* **l**

Table 3.1 Synthesis of mandelate and lactate esters (*: synthesised by BP)

3.2.2 Step 1: Esterification – Synthesis of α-bromoesters

The synthesis of the alkylating agents proceeded in average to good yield, loss in yield being due to the purification step required (Table 3.2).

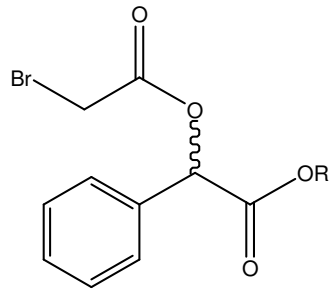
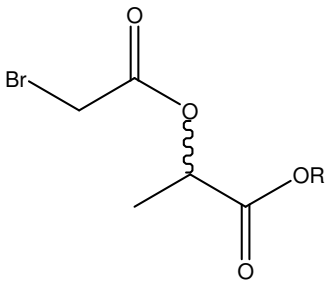
Mandelate derivative **211**				Lactate derivative **212**		
						
R:	***R***	***S***	***RS***	**R:**	***R***	***RS***
	58* **m**	69* **n**	73 **o**	CH_3	59 **a**	37 **b**
C_2H_5	69 **a**	66 **b**	90 **c**	C_2H_5	41* **c**	57 **d**
	-	-	-	C_3H_7	82* **e**	70* **f**
C_4H_9	80 **d**	69 **e**	75 **f**	C_4H_9	35* **g**	40 **h**
C_5H_{11}	57 **g**	37 **h**	63 **i**	C_5H_{11}	58* **i**	33* **j**
$C_2H_4OC_2H_5$	76 **j**	65 **k**	65 **l**	$C_2H_4OC_2H_5$	58* **k**	60* **l**

Table 3.2 Synthesis of mandelate and lactate α-bromoesters (*: synthesised by BP)

Purification of the crude mandelate-based bromoesters involved column chromatography. DCM : hexane proved to be the best mobile phase for most mandelate derivatives in varying proportions, ranging from 50 : 50 DCM : hexane, for ethyl derivatives, to 70 : 30 DCM : hexane, for pentyl and 80 : 20 DCM : hexane for ethoxytethyl side-chain derivatives. The pure product was the last spot to elute from the column, generally as a pale yellow oil. Analysis of the ^{1}H NMR spectra of the pure products obtained for this step of the synthesis display interesting features. As can be noted in the case of both the mandelate and lactate derivatives (Table 3.3), the signal for the proton (integration = 1) shifts by approximately 0.8 ppm in both cases, upon formation of the bromoester, as the other signals remain at approximately the same chemical shift. This is thought to be due to the increased electronegativity of its environment due to the addition of the bromoester moiety.

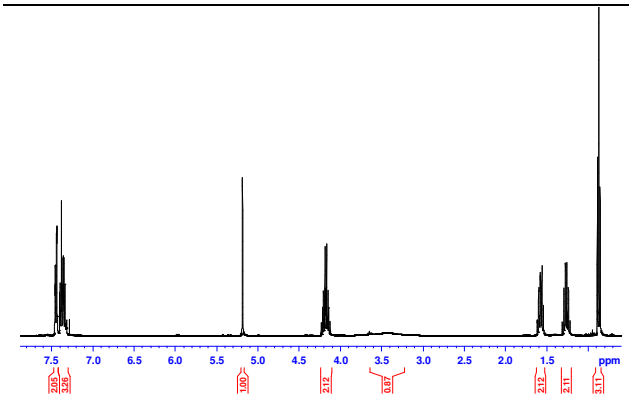
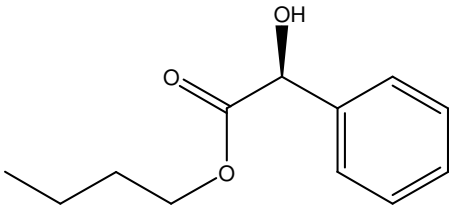
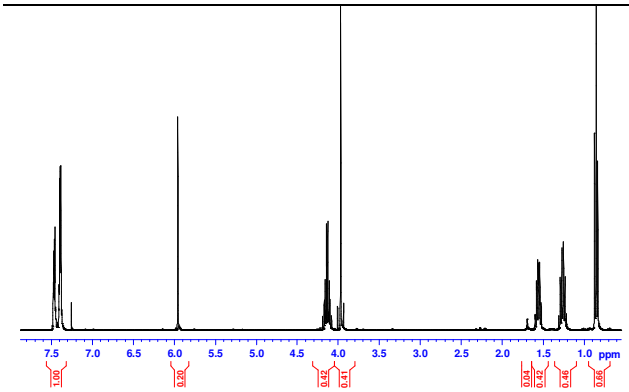
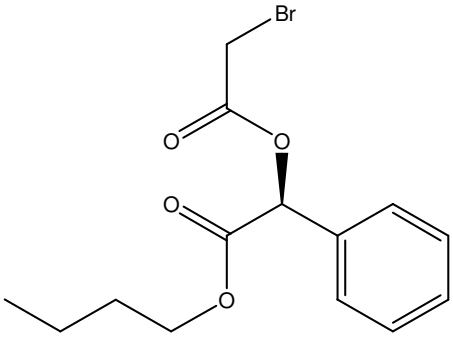
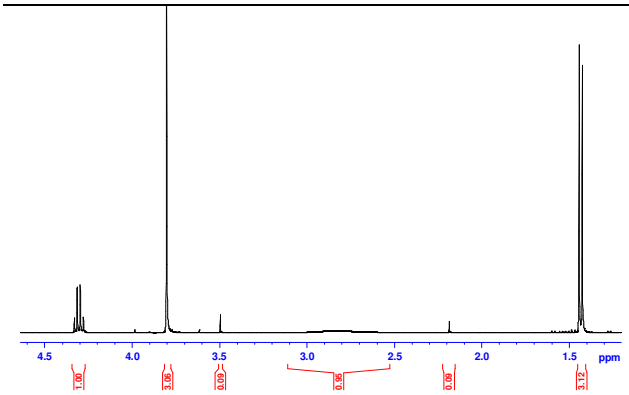
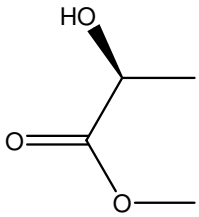
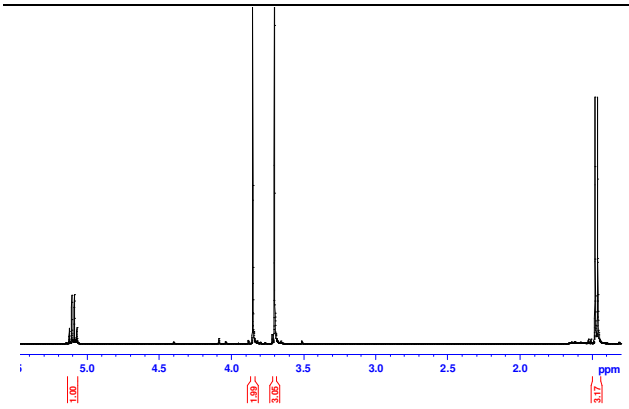
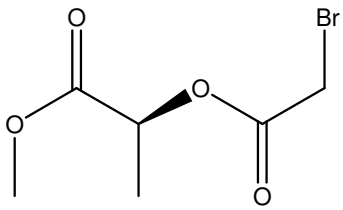
		**209d**
		**211d**
		**210a**
		**212a**

Table 3.3 Chemical shift investigation of ^{1}H NMR spectra

More importantly to note is the appearance of a doublet in the spectrum of the mandelate bromoester (Figure 3.6). These signals, due to diastereotopic protons, display evidence of the roofing effect.

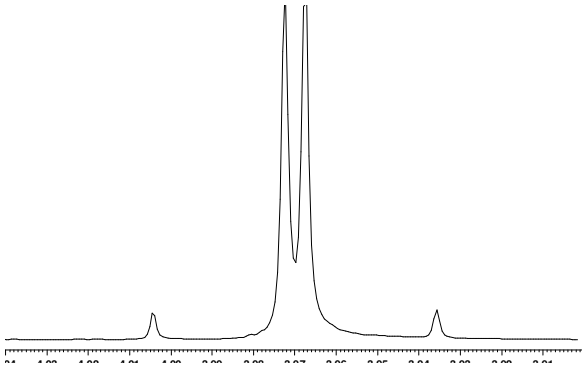


Figure 3.6 Roofing effect

3.2.3 Step 2: Alkylation – Synthesis of imidazolium bromide salts

The synthesis of the bromide salts proceeded in good yields (Table 3.4). Synthesis of the lactate bromide derivatives yielded viscous liquids at RT. The same reaction conditions were used for the synthesis of these bromide salts, as were used for the synthesis of the achiral derivatives.

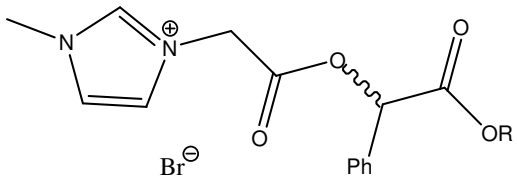
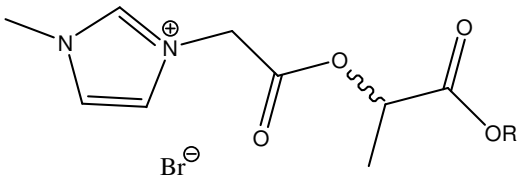
Mandelate derivative **213** 				Lactate derivative **214** 		
R:	***R***	***S***	***RS***	**R:**	***R***	***RS***
CH_3	93 **m** **99-101 °C**	78 **n** **97-99 °C**	94 **o** **140-142 °C**	CH_3	66 **a** **115-117 °C**	50*__b__
C_2H_5	81 **a** **130-132 °C**	82 **b** **129-131 °C**	68 **c** **132-134 °C**	C_2H_5	77 **c**	88 **d**
	-	-	-	C_3H_7	87*__e__	88 **f**
C_4H_9	82 **d** **88-90 °C**	64 **e** **89-91 °C**	58 **f** **118-120 °C**	C_4H_9	86 **g**	82 **h**
C_5H_{11}	68 **g** **44-45 °C**	73 **h** **73-75 °C**	60 **i** **127-129 °C**	C_5H_{11}	89*__i__	87*__j__
$C_2H_4OC_2H_5$	71 **j** **31-33 °C**	85 **k**	76 **l** **124-126 °C**	$C_2H_4OC_2H_5$	84*__k__	95*__l__

Table 3.4 Mandelate and lactate bromide salts (*: synthesised by BP)

The coupling of diastereotopic protons in the spectrum of **214a** as an example can be seen in Figure 3.7. H_1 and H_2 protons are in inequivalent environments. They are thus coupling with each other, to give two different sets of doublet signals. Here also is an example of the roofing effect, which shows us that these two protons are strongly coupled.

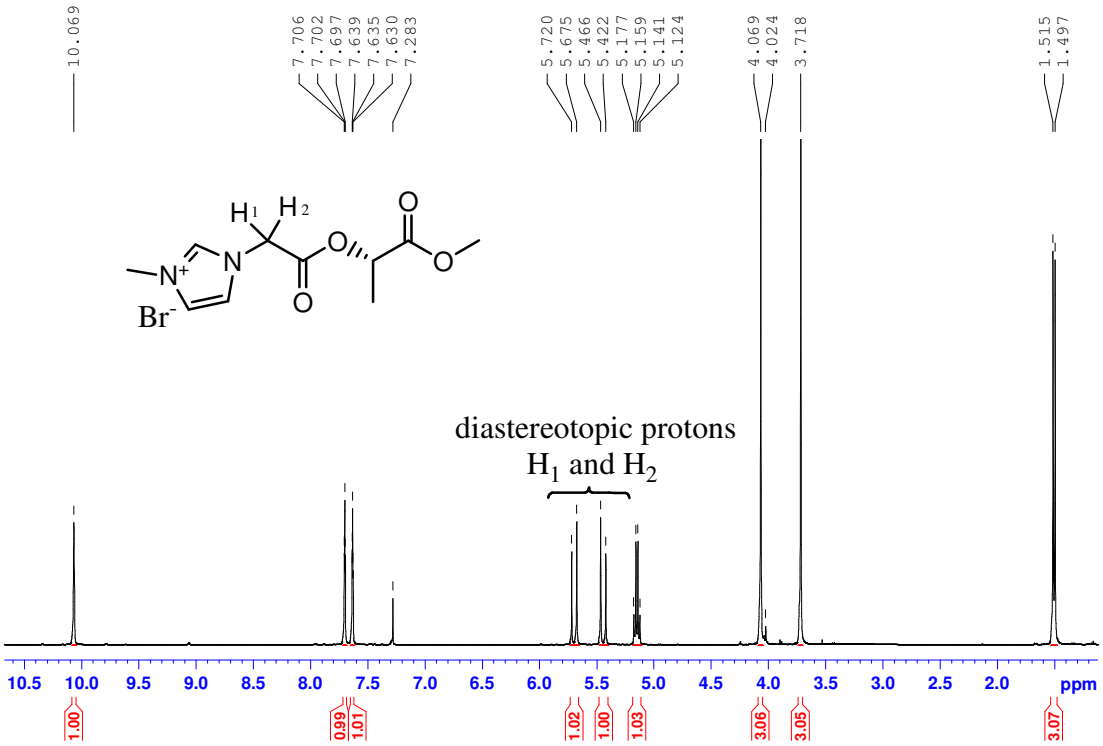


Figure 3.7 ^{1}H NMR of **214a**

Further evidence of the mutual coupling of these two methylene protons can be seen in the COSY NMR spectrum of this bromide salt **214b** (Figure 3.8).

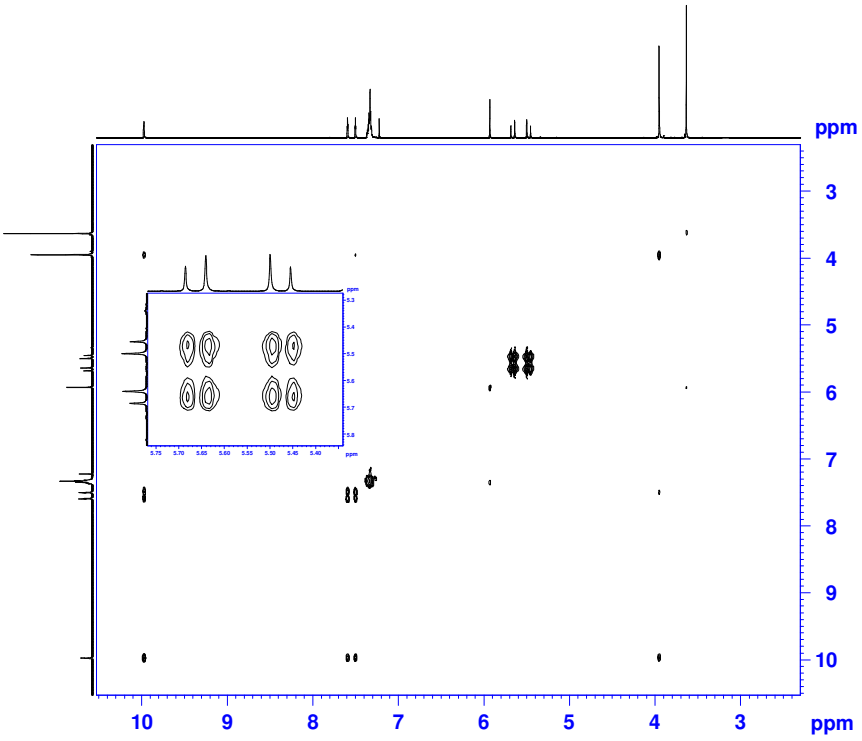


Figure 3.8 COSY spectrum of **214b**

An increase in melting point was observed in the case of the mandelate bromide derivatives with the formation of solid powders at RT. An example of a ^{1}H NMR spectrum of a typical bromide mandelate based salt, namely the butyl derivative, (**213e**) can be seen in Figure 3.9.

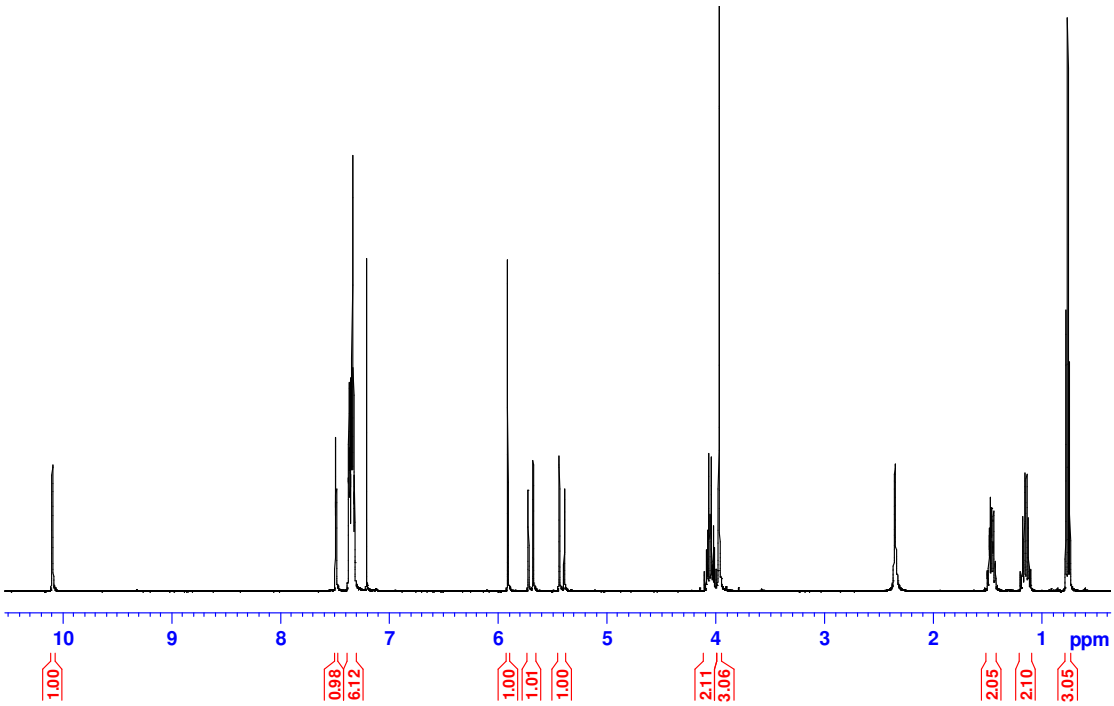


Figure 3.9 3-methyl-1-(*S*)-(butylmandelylcarbonylmethyl)imidazolium bromide **213e**

The same roofing effect can be seen here as was noted for the lactate derivatives at approximately 5.5 ppm.

An interesting effect can be seen from examining the signals from the ^{1}H NMR of these particular diastereotopic protons. As in the case of the achiral ILs, the charge separation between the anion and the cation may be estimated from the signals of these protons. Again, the deshielding effect of the anion can be viewed. The greater deshielding effect the anion has on the cation of the IL, the greater the distance between the two inner signals. The more deshielded the cation, the more influential the effect of the adjacent chiral centre is. The same trend of anion effect on charge separation as was demonstrated with the achiral ILs is now evident: $\Delta\delta$ is greatest for the bromide salts, this value is less for the [$OctOSO_3$] derivatives, and is the least for the [NTf_2] derivatives. Therefore, the more deshielded the protons, the weaker their mutual coupling. With the ILs of the bromide anion, $\Delta\delta$ is the largest. Also, the chemical shift for these protons, taking as an example *RS*-ethyl mandelate, are the lowest downfield for the bromide salt (~5.6 ppm) (**213a**), more upfield (~5.3 ppm) for [$OctOSO_3$] (**217a**)

and the most upfield for the [NTf_2] salt (**215a**) (~5.0 ppm). From examining the spectra of **213a** and **215a,** it can be seen that the distance measured between the two inner signals for the methylene protons of the bromide salt is 0.195 ppm, whereas the spectrum of the [NTf_2] salt shows the overlapping of these peaks to form one peak. The effect for the [$OctOSO_3$] ILs can be seen when the distance between signals displaying the roofing effect in the spectrum of **217a** are less than 0.195 but greater than 0, which is the case for the [NTf_2] derivative of this IL.

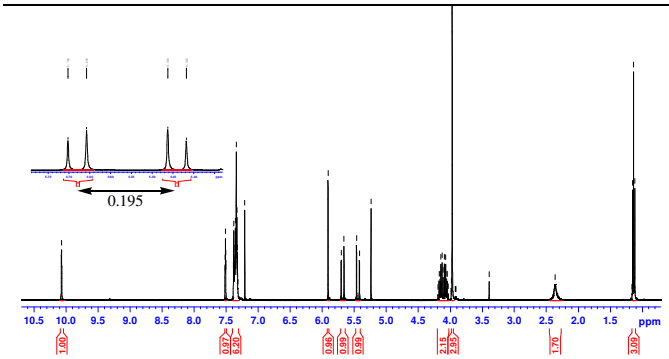
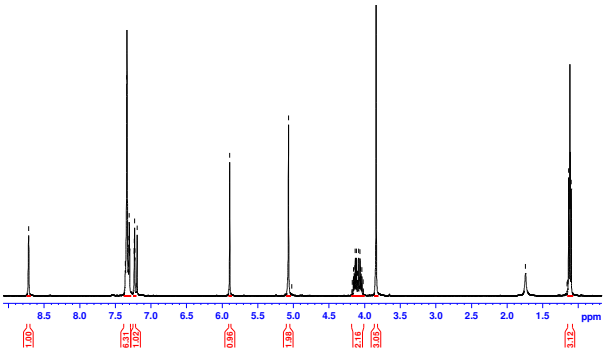
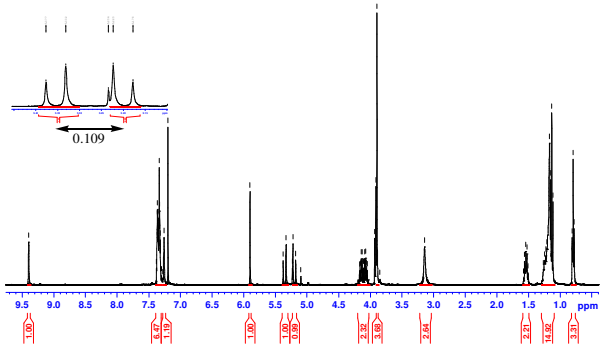
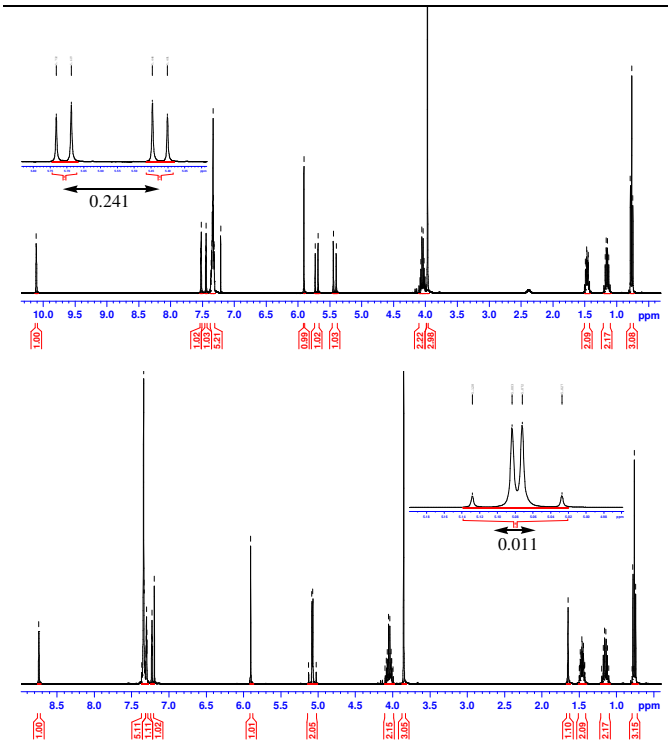
	**213a**
	**215a**
	**217a**

Table 3.5 Comparison of chemical shift differences of diastereotopic protons

In the case of the (*S*)-butyl mandelate derivative ([Br] **213e** and {NTf_2] **215e**), the signals for the [NTf_2] IL display the roofing effect, Δδ being however much less in the case of the [NTf_2] salt in comparison with the bromide derivative.



213e

215e

Table 3.6 Comparison of chemical shifts of diastereotopic protons

With the use of this method however evolved problems concerning the formation of the mandelate bromide salt. Upon addition of the bromoester, to the stirred solution of methyl imidazole in diethyl ether, brown/black viscous material gradually appeared. An example spectrum of this impure material in comparison with the pure product can be seen in Figure 3.10.

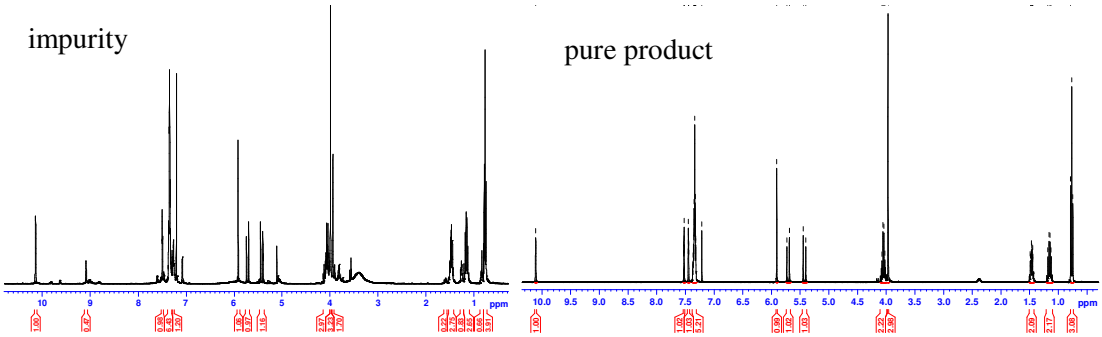


Figure 3.10 ^{1}H NMR of impurity spectrum and pure product (**213e**)

The main difference noted between this spectrum and the spectrum of the pure product, is that the impure viscous material bears the same peaks as the pure material, however containing extra impurity peaks. A conspicuous extra peak at 9.1 ppm could suggest remaining methyl imidazole in the viscous material. The broad band occurring at 3.4

ppm however may suggest that some moisture entered the reaction flask thus resulting in hydrolysis and the starting alcohol being present. This material was occasionally observed appearing at the start of the reaction, whilst still at – 20 ºC, but often time seen as the reaction mixture was warmed up to room temperature. Progression of the reaction showed formation of lightly coloured to white powders forming, separately to the impurity. Numerous attempts were made to curb the formation of this impurity. The reaction temperature was lowered to - 78 ºC for the dropwise addition of the bromoester with no change observed. Slower addition of the bromoester to the stirring solution of 1-methylimidazole also resulted in no change observed. An alternative addition method was attempted; i.e. dropwise addition of 1-methylimidazole to a stirring solution of bromoester however no change was observed. On occasion, when the pure product was the first observed to be forming at the reduced temperature, the reaction was allowed to warm up to just below room temperature and then stopped. Although this effort led to the formation of only one pure product, a huge compromise in yield was observed, the bromide salts, although being pure, obtained in this manner being present in approximately 5 % yield. The reaction solvent was exchanged from diethyl ether to THF, however again, no change was observed. The bromoester was added dropwise at RT, with no change observed. 1-methylimidazole was added dropwise at RT to the reaction solvent containing the bromoester, but still the impurity was observed.

As the synthesis of these bromide salts progressed, it was noticed that the impurity was only formed on very small scale relative to the formation of the product, and due to the differing natures of the two materials, could easily be separated from each other during the reaction work-up. It was also observed on occasion, that no impurity formed during reaction, and thus many bromide salts were formed in almost 100 % purity. Thus, efforts to optimise this method by eliminating the formation of the impure material were abandoned, as the pure product could be obtained in satisfactory yields.

The one exception to this occurrence was the case of the (*S*) – ethoxyethyl mandelate bromide derivative (**213k**). This was formed as a viscous liquid, NMR analysis showing it to contain the undesired impurity (Figure 3.11).

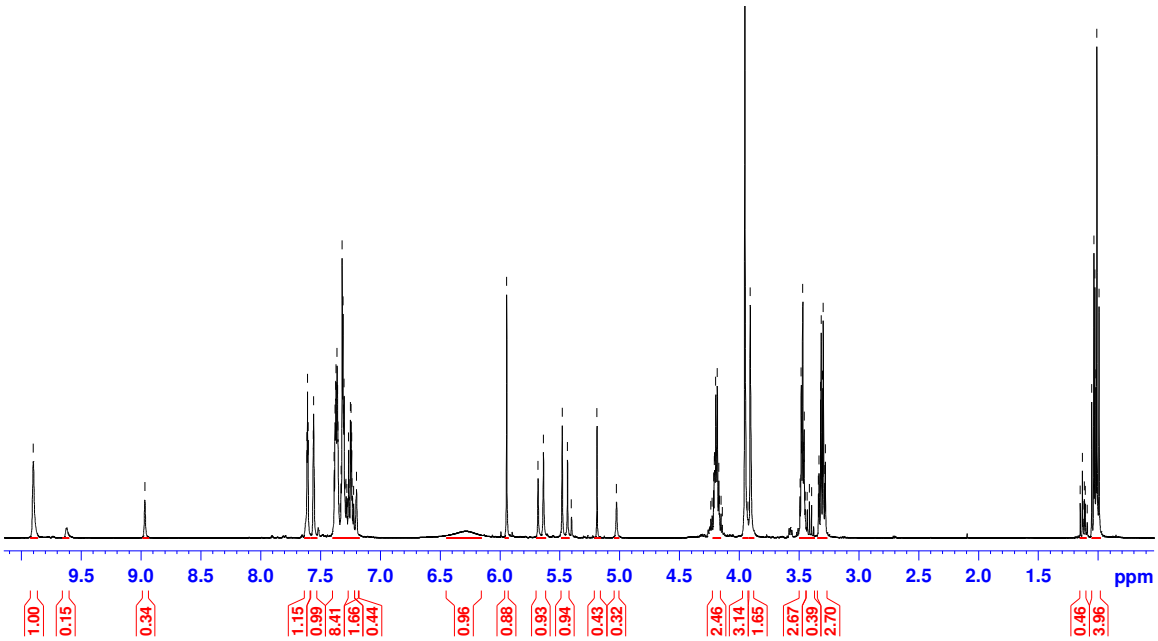


Figure 3.11 ^{1}H NMR spectrum of **213k**

Although the *R*- (**213j**) and *RS*- (**213l**) versions of this salt proceeded as expected, with the formation of powders, the nature of the *S*- (**213k**) version rendered it impossible to separate from this impurity using the current purification method. **213k** was however used for the synthesis of the [NTf_2] salt (**215k**). It was hoped that these impurities would be water soluble, and indeed some impurity was eliminated with the water washes. A spectrum of the **215k** can be seen below (Figure 3.12). Although not as pure as other mandelate [NTf_2] salts formed, a decrease in impurity can be observed in comparison with the spectrum for the corresponding bromide salt (**213k**).

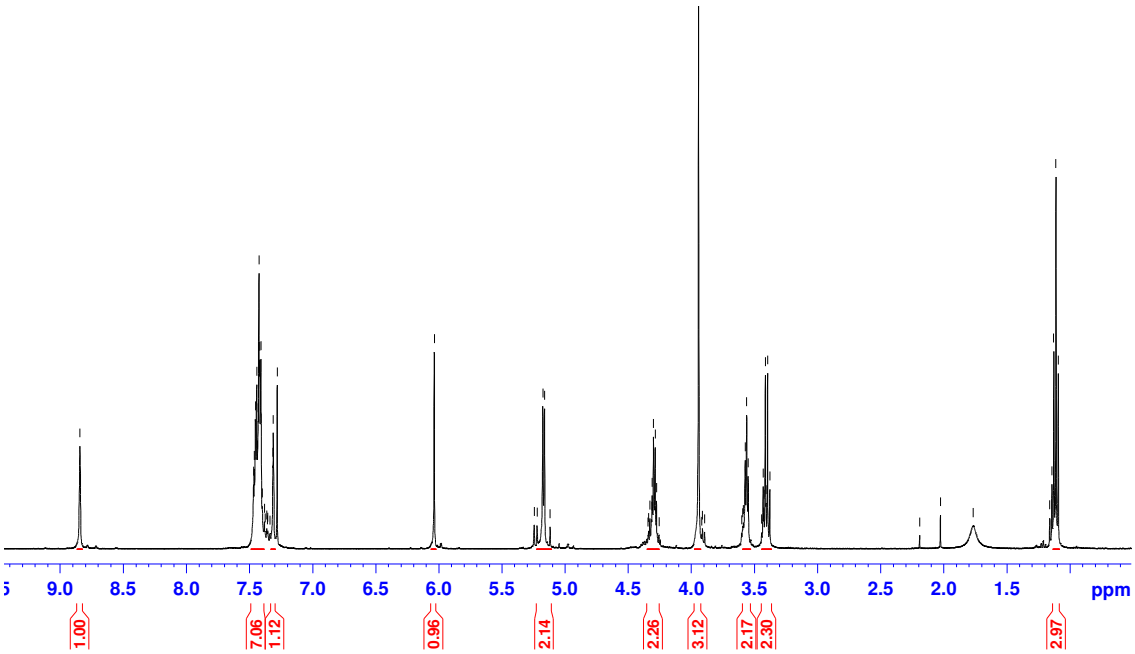


Figure 3.12 ^{1}H NMR spectrum of **215k**

3.2.4 Step 3: Anion metathesis

3.2.4.1 [NTf_2] ILs

Synthesis of the chiral [NTf_2] salts remained unchanged from the synthesis of their achiral counterparts. Depressed melting points in comparison to their bromide salt derivatives were again observed. Reactions proceeded in good to excellent yields for both mandelate (79 -98 %) and lactate (57 – 92 %) derivatives (Table 3.7).

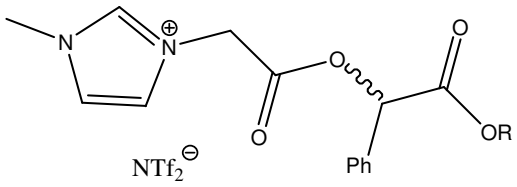
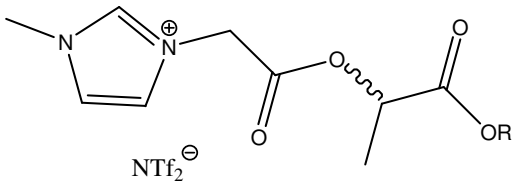
Mandelate derivative **215**				Lactate derivative **216**		
						
R:	***R***	***S***	***RS***	**R:**	***R***	***RS***
CH_3	- **m**	- **n**	92 **o** **73-75 °C**	CH_3	57 **a**	65 **b**
C_2H_5	95 **a** **44-46 °C**	85 **b** **44-46 °C**	95**c**	C_2H_5	72 **c**	63 **d**
				C_3H_7	92 **e**	86 **f**
C_4H_9	98 **d**	93 **e**	94 **f**	C_4H_9	64 **g**	83 **h**
C_5H_{11}	87 **g**	96 **h**	93 **i**	C_5H_{11}	87 **i**	87 **j**
$C_2H_4OC_2H_5$	92 **j**	86 **k**	79 **l**	$C_2H_4OC_2H_5$	67 **k**	76 **l**

Table 3.7 Mandelate and lactate derived [NTf_2] ILs

From the example spectra shown for **214a** and **216a** (Table 3.8), it can be seen that the signals due to the imidazolium moiety of the cation are shifted upfield in the case of the spectra for the [NTF_2] salt, from 7.6 ppm to 7.4 ppm. The acidic proton signal of the imidazolium ring is also more downfield in the case of the bromide salt. Also shifted upfield in the case of [NTf_2] are the signals for the inequivalent methylene protons. Other signals however remain at approximately the same chemical shift for each salt. Thus it is evident that it is only these protons that experience a greater influence from deshielding by the anion.

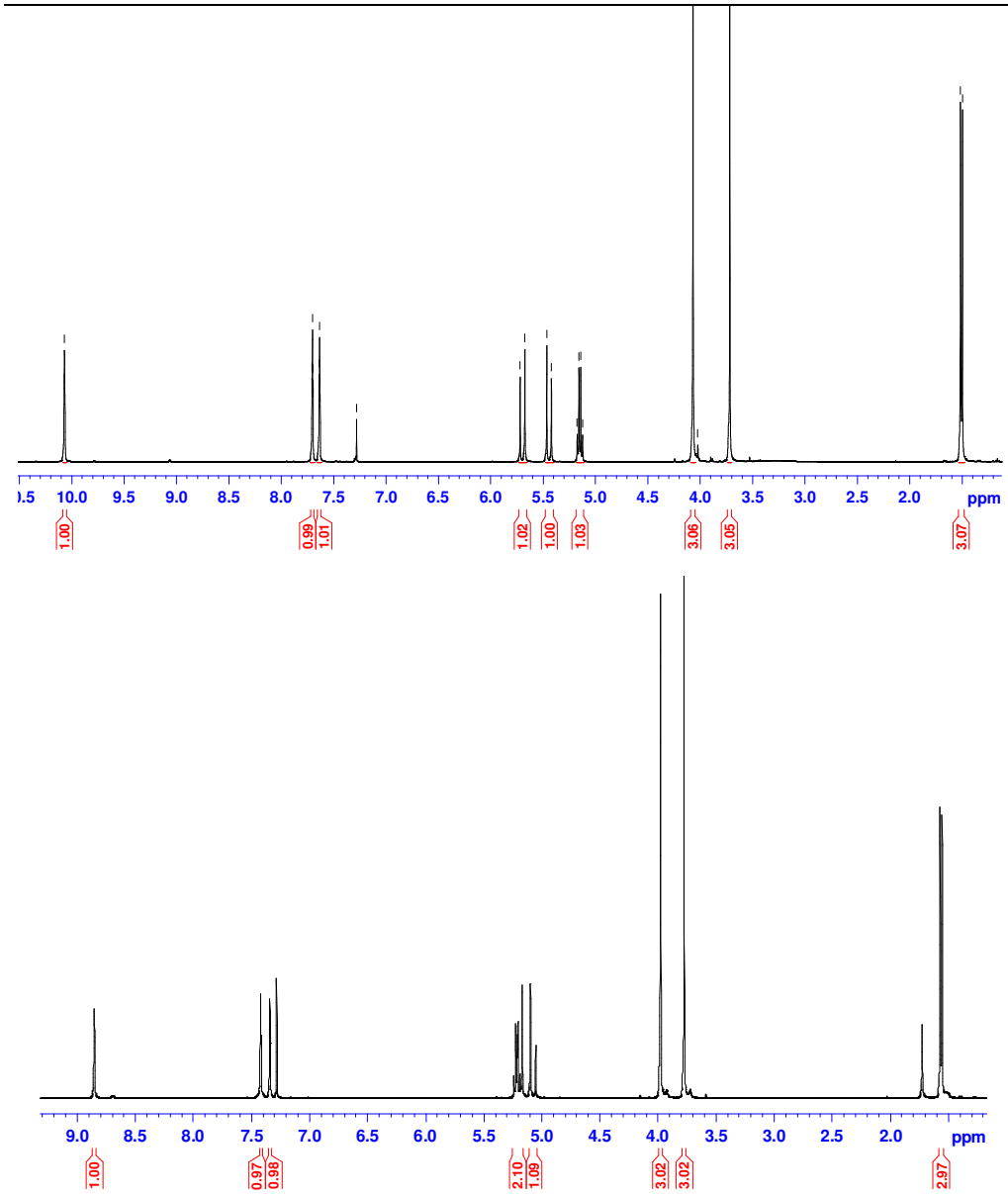


Table 3.8 Chemical shift comparison of ILs of different anions

In the case of the mandelate derivatives, as can be seen for **213f** and **215f**, the same effect is evident. The signals in the aliphatic region of the spectrum remain more or less unchanged from the bromide to the [NTf_2] salt. The signal for the aromatic protons also remains unchanged. The signal due to the methyl group bound to the imidazolium ring shows a minor downfield shift (~ 0.1 ppm) in the spectrum of the bromide salt in comparison to that of the [NTf_2] salt.

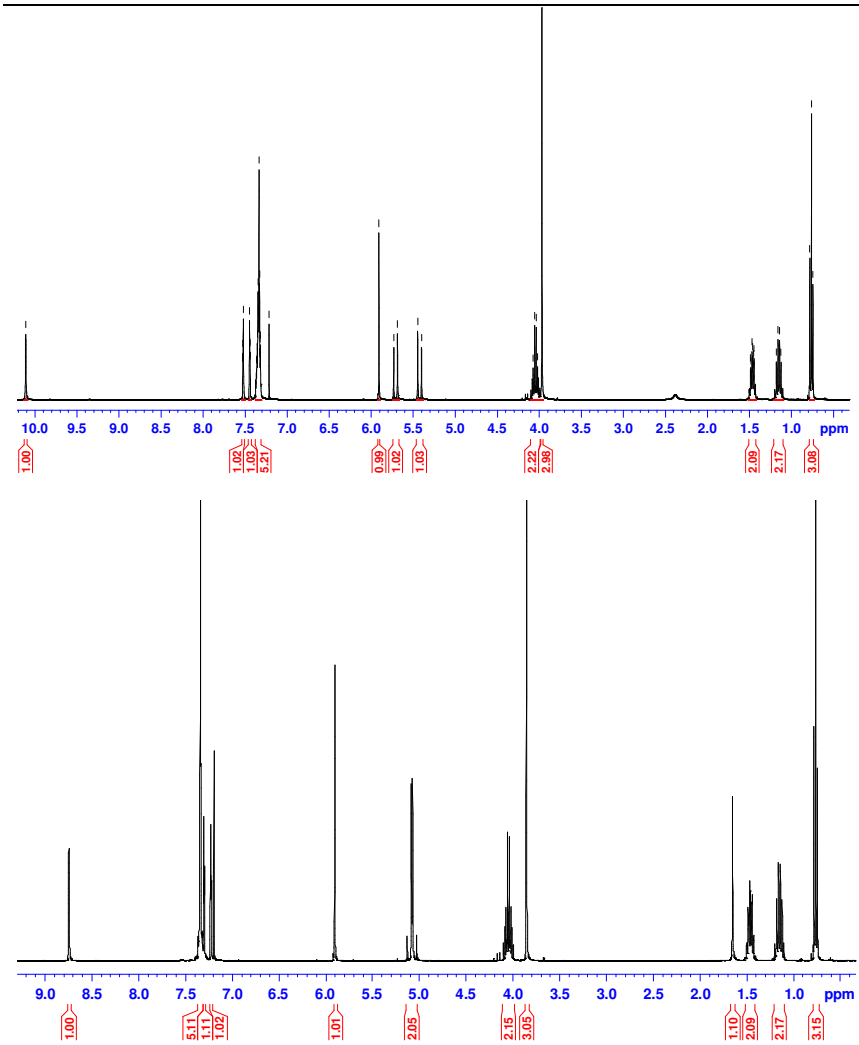


Table 3.9 Comparison of chemical shift values for ILs of different anions

The roofing effect is also much more significant in the case of the counterion exchange salt **215f** (Figure 3.13).

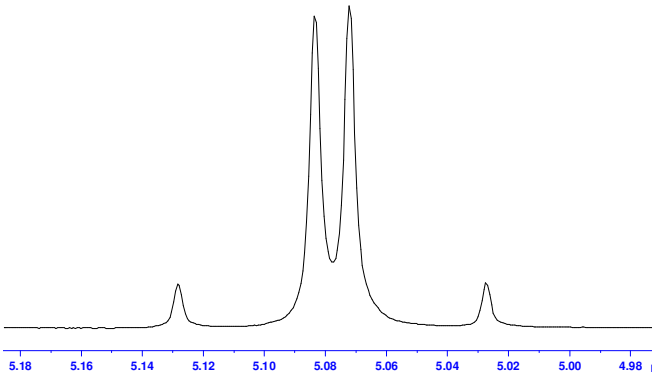


Figure 3.13 Roofing effect in ^{1}H NMR spectrum of **215f**

3.2.4.2 [OctOSO$_3$] ILs

The method used for the synthesis of the achiral [OctOSO$_3$] salts was modified slightly for the formation of the chiral derivatives. A reaction was initially carried out under the same conditions as used for the achiral salts (H_2O, 60 º, and 2 h). The resulting ^{1}H NMR obtained from this reaction showed a hydrolysis reaction having occurred due to the increased temperature and presence of water in the reaction. The reaction was therefore carried out at RT with an extended reaction time (from 2 h to overnight) in order to ensure reaction completion. This indeed resulted in the formation of the pure products with no compromise in yield (71 – 99 %) for mandelate salts and 87 – 95 % for the lactate derivatives (Table 3.10).

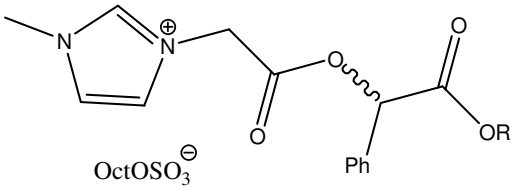
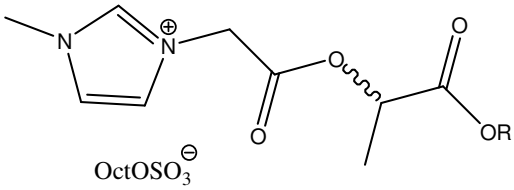
Mandelate derivative				**Lactate derivative**		
217				**218**		
						
R	***R***	***S***	***RS***	**R**	***R***	***RS***
CH_3	75* **m**	89* **n**	97 **o**	CH_3	94 **a**	90* **b**
C_2H_5	95 **a**	91 **b**	92 **c**	C_2H_5	93* **c**	95* **d**
	40-42 ºC	**38-40 ºC**				
				C_3H_7	90* **e**	89* **f**
C_4H_9	98 **d**	77 **e**	99 **f**	C_4H_9	89* **g**	90 **h**
		30-32 ºC				
C_5H_{11}	99 **g**	99 **h**	95 **i**	C_5H_{11}	87* **i**	89* **j**
	29-31 ºC		**30-32 ºC**			
$C_2H_4OC_2H_5$	82 **j**	71 **k**	83* **l**	$C_2H_4OC_2H_5$	90 **k**	91* **l**

Table 3.10 Mandelate and lactate derived [OctOSO$_3$] salts

3.3 Biodegradation Studies

Biodegradation studies were carried out on the novel [OctOSO$_3$] CILs. (Toxicity testing was not performed in advance due to time constraints regarding patent filing.) In comparison with the achiral counterparts of the chiral ILs, the lactate derivatives demonstrate similar biodegradation values to the achiral ILs. The most noticeable difference was observed with the addition of a phenyl group to the ILs as in the case of

the mandelate derivatives. Higher biodegradation percentages were obtained from the mandelate derivatives after 28 days in comparison with the lactate derivatives.

3.3.1 Mandelate derivatives

All mandelate ILs were readily biodegradable. Regarding the effect of the side chain length on the biodegradation of the mandelate derivatives, not much difference is evident between the [$OctOSO_3$] salts. The most prominent result was obtained from the ethyl derivative which displayed the lowest biodegradation of the mandelate derivatives. No significant variation was evident between the same ILs of different enantiomeric composition except for the ethoxyethyl derivative. The racemic form of this [$OctOSO_3$] IL gave 68 % however its enantiomeric forms display significantly higher biodegradation after 28 days equal to or exceeding 80 %.

IL no.	Days					IL no.	Days				
	0	**7**	**15**	**21**	**28**		**0**	**7**	**15**	**21**	**28**
SDS	0	79	85	89	89	**217f***	0	66	75	83	82
217m	0	58	66	70	77	**217g**	0	64	78	79	82
217n	0	62	68	70	71	**217h**	0	62	72	77	79
217o	0	58	64	69	74	**217i**	0	66	76	81	79
217a	0	50	58	65	65	**217j**	0	51	62	68	68
217b*	0	51	62	67	67	**217k**	0	63	73	78	80
217d	0	62	71	78	78	**217l**	0	73	77	85	83

Table 3.11 Biodegradation of Mandelic [$OctOSO_3$] ILs

* ILs **217 c** and **e** were omitted from this study due to funding constraints

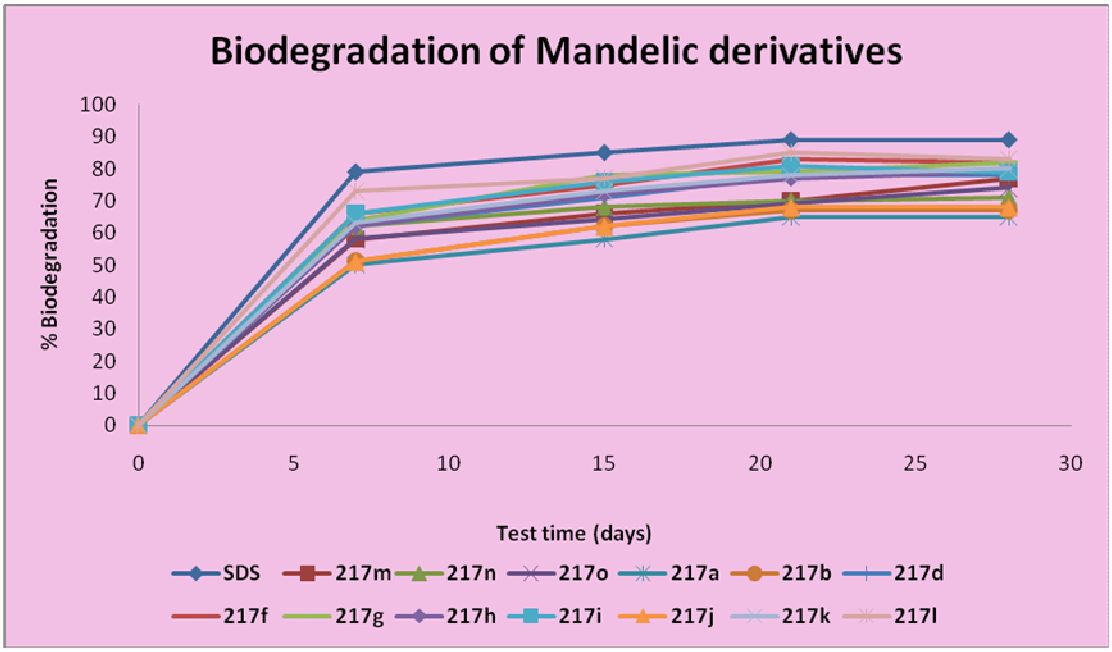


Figure 3.14 Biodegradation of Mandelic [$OctOSO_3$] ILs

3.3.2 Lactate derivatives

Nine out of twelve lactate ILs tested were readily biodegradable. Again, as with the mandelate derivatives, the ethyl derivative of the lactate [$OctOSO_3$] ILs demonstrated the lowest biodegradation result. The greatest difference evident between the racemic form and enantiomeric form of a lactate IL of the same side chain length was observed with the butyl derivative. A difference of 7 % was observed between the two forms of this [$OctOSO_3$] IL.

IL no.	Days					IL no.	Days				
	0	**7**	**15**	**21**	**28**		**0**	**7**	**15**	**21**	**28**
SDS	0	76	85	86	89	**218g**	0	52	61	58	61
218a	0	46	57	61	64	**218h**	0	41	51	50	55
218b	0	49	60	63	67	**218i**	0	52	65	72	72
218c	0	44	54	52	56	**218j**	0	54	67	70	71
218d	0	41	53	51	59	**218k**	0	55	64	69	69
218e	0	50	63	66	67	**218l**	0	59	69	74	74
218f	0	51	62	69	69						

Table 3.12 Biodegradation of Lactate [$OctOSO_3$] ILs

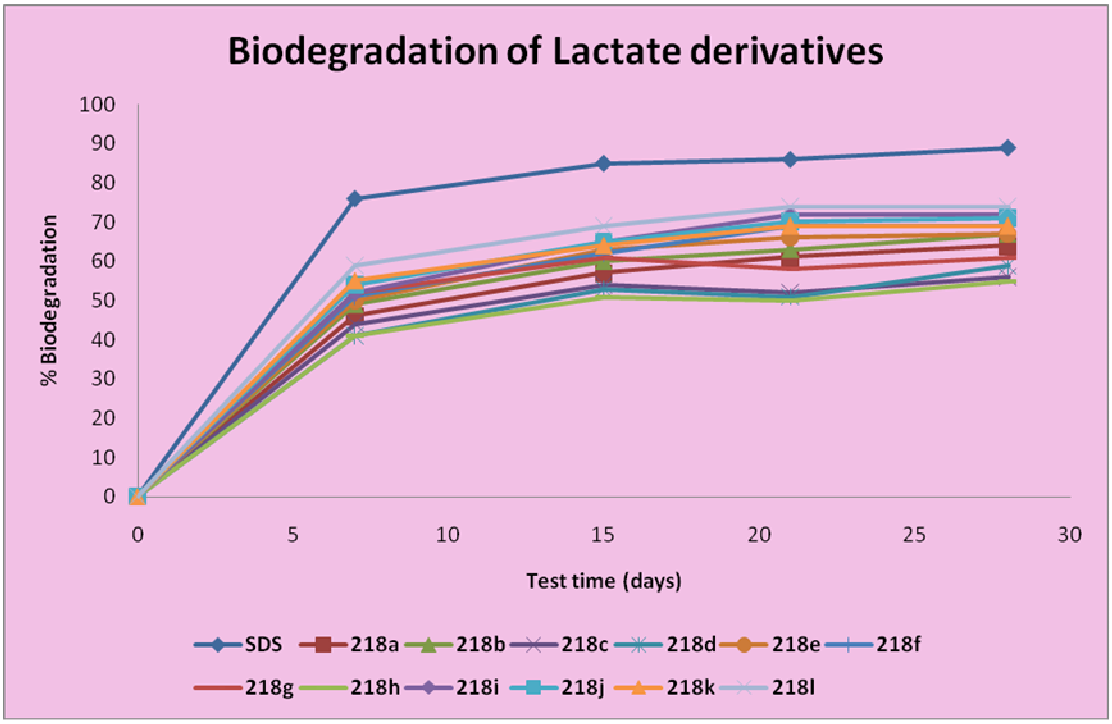


Figure 3.15 Biodegradation of Lactate [$OctOSO_3$] ILs

3.4 Structural studies of enantiomers (213m and n) of ILs

Crystals suitable for crystallographic analysis were grown from (*R*) and (*S*) enantiomers, **213m** and **213n**. **213m** was grown in an NMR tube from a saturated solution of the product in dichloromethane to give small slightly yellow oblong-shaped crystals. A binary solvent system consisting of dichloromethane and hexane was used to grow colourless block-shaped crystals of **213n**.

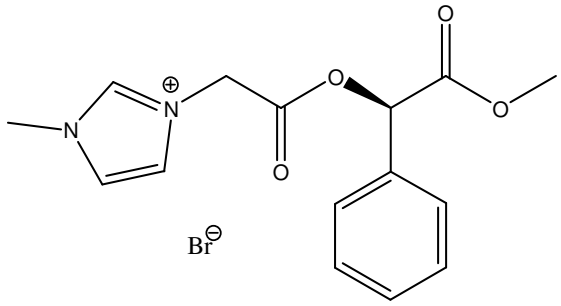
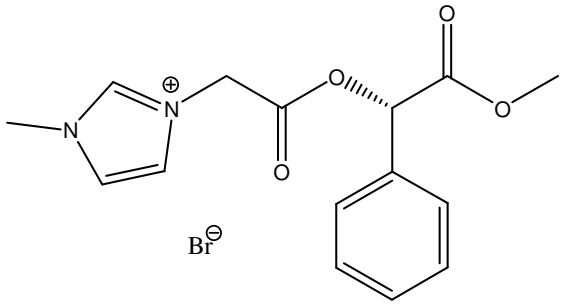
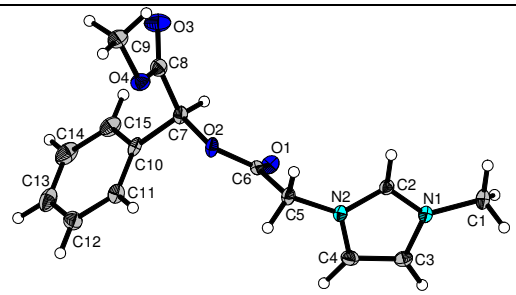
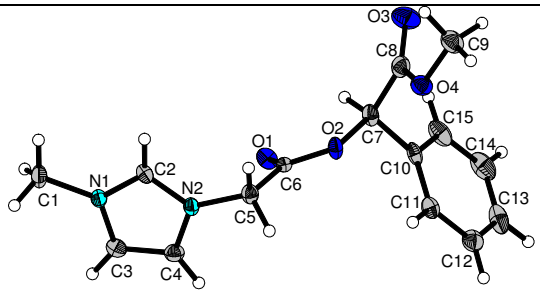
213m	213n
	
	

Table 3.13 Crystal structures of enantiomeric forms of **213m** and **213n**

Both **213m** and **213n** crystallise in the triclinic space group P1 and contain two ionic pairs per asymmetric unit. Both crystals contain a water molecule hydrogen bonded to the bromine atoms in the crystallographic lattice.

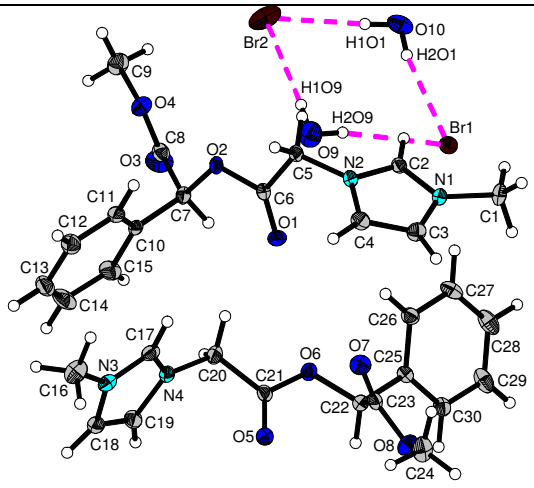
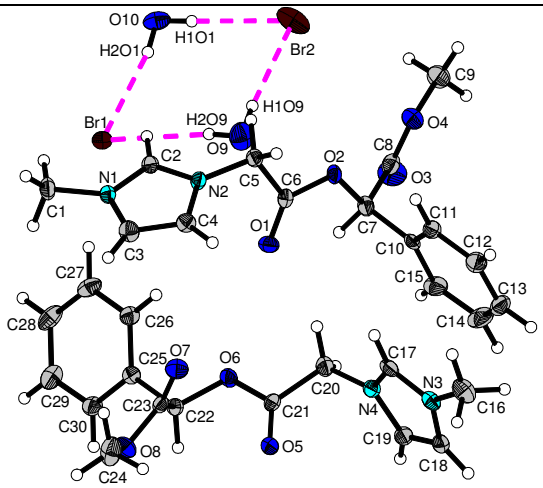
213m	213n
	

Table 3.14 Molecules with the counter ions and the hydrogen bond linked water molecules

Comparing the data collected from both crystal structures, both enantiomers are almost identical. Taking **213m** as an example, the aromatic character of the imidazole ring can

be identified. The C-C bond length in the imidazole ring (C_4-C_5: 1.356 Å) is similar to the C-C bond lengths of the aromatic phenyl group which range from 1.370 to 1.397 Å. These aromatic bond lengths are substantially less than the C-C bond length of a non-aromatic carbons (C_7-C_{10}: 1.514 Å).

3.5 Conclusion

From the library of compounds prepared, from 24 starting materials, 13 mandelate esters and 2 lactate esters were prepared. The remaining compounds in the library were prepared by BP (*). 13 mandelate and 4 lactate bromoesters were prepared out of a possible 24. 15 mandelate and 6 lactate bromide salts, 13 mandelate and 12 lactate [NTf_2] ILs and 12 mandelate and 3 lactate [$OctOSO_3$] ILs were prepared. The starting materials were synthesised in pure form in order to synthesise all chiral ILs for this library of compounds. It was found that chirality could indeed be integrated into these ILs by this method. The novel ILs were characterized by ^1H and ^{13}C NMR and by mass spectrometry. The melting points for the mandelate bromide salts however were in some cases above the currently defined range for ILs (> 100 °C), the changing of the counter ion to [NTf_2] or [$OctOSO_3$] was shown to lower the melting point to within this range. The biodegradability of all the chiral mandelate ILs was found to be above the pass level for the test, > 60 %. For nine out of twelve chiral lactate examples, they also passed the CO_2 Headspace test. The three ILs which were not found to be readily biodegradable gave 55-59 %.

3.6 Bibliography

1 G. Blaschke, H. P. Kraft, H. Markgraf, *Chem. Ber.,* 1980, **113**, 2381.

2 Lee, E. J. D., K. Williams, R. Day, G. Graham and D. Champion, *Br. J. Clin. Pharmacol.,* 1985, **19**, 669.

3 W. F. Kean, H. E. Howard-Lock and Lock, C. J. L., *The Lancet,* 1991, **338**, 1565.

4 D. Mormeneo, J. Casas, A. Llebaria and A. Delgado, *Org. Biomol. Chem.,* 2007, **5**, 3769.

5 A. Madhavi, G. Reddy, M. Suryanarayana and A. Naidu, *Chromatographia,* 2008, **67**, 633.

6 G. C. Hargaden, T. P. O'Sullivan, and P. J. Guiry, *Org. Biomol. Chem.,* 2008, **6**, 562.

7 R. Gausepohl, P. Buskens, J. Kleinen, A. Bruckmann, C. Lehmann, J. Klankermayer and W. Leitner, *Angew. Chem. Int. Ed.,* 2006, **45**, 3689.

8 S. Huttenhain, M. Schmidt, F. Schoepke and M. Rueping, *Tetrahedron,* 2006, **62**, 12420.

9 P. Mukhopadhyay, G. Zuber, P. Wipf and D. Beratan, *Angew. Chem. Int. Ed.,* 2007, **46**, 6450.

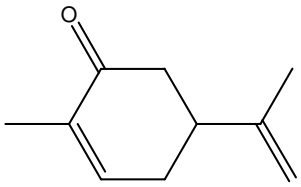
10 A. E. Moormann, B. S. Pitzele, P. H. Jones, G. W. Gullikson, D. Albin, S. S. Yu, R. G. Bianchi, E. L. Sanguinetti, B. Rubin, M. Grebner, M. Monroy, P. Kellar, J. Casler, *J. Med. Chem.,* 1990, **33**, 617.

4 Application of novel achiral ILs in hydrogenation reactions

4.1 Introduction

With current increased environmental awareness, hydrogenation is an especially popular reduction reaction, as hydrogen gas is an inexpensive reagent and by far the cleanest reducing agent.[1] Also, hydrogenation in the form of heterogeneous catalysis facilitates facile catalyst separation from the desired product and in some cases catalyst recycling.

Hydrogenation is used to reduce various functional groups. This reaction is widely used throughout the petrochemical industry[2] as well as being used extensively in the synthesis of products and intermediates for the pharmaceutical industry.[3, 4] Heterogeneous hydrogenation is advantageous over homogeneous hydrogenation, because in the liquid phase, the catalyst can be separated and regenerated and thus the products isolated in their pure form. Selective hydrogenation is important as often there are many reducible functionalities present in a compound. A prime example is the terpene, carvone (**219**) (Figure 4.1). It has three possible reduction sites, the carbonyl group, and both endo-cyclic and exo-cyclic olefinic groups, with products of its selective hydrogenation being desirable.[5-8]



carvone
219

Figure 4.1 Carvone (**219**)

The classic metals used for hydrogenation are noble metals, for example palladium and platinum, finely distributed on solid supports such as activated carbon.

Using heterogeneous hydrogenation, a destructive form of hydrogenation can be achieved – hydrogenolysis. A common use of hydrogenolysis is for removal of protecting groups such as benzyl ethers[9] or silyl ethers (TMS – trimethylsilyl or TBDMS – tert-butyldimethylsilyl).[10]

The hydrogenation at 1 atm H_2 pressure of various substrates (*trans*-stilbene (**220**), *trans*-cinnamaldehyde (**94**), *trans*-cinnamic acid (**221**), methyl cinnamate (**222**), ethyl *trans*-cinnamate (**223**), benzyl cinnamate (**224**), cinnamonitrile (**225**), cinnamamide

(**226**), allyl cinnamate (**227**), vinyl cinnamate (**228**)) in a range of novel achiral ILs was investigated (Figure 4.2).

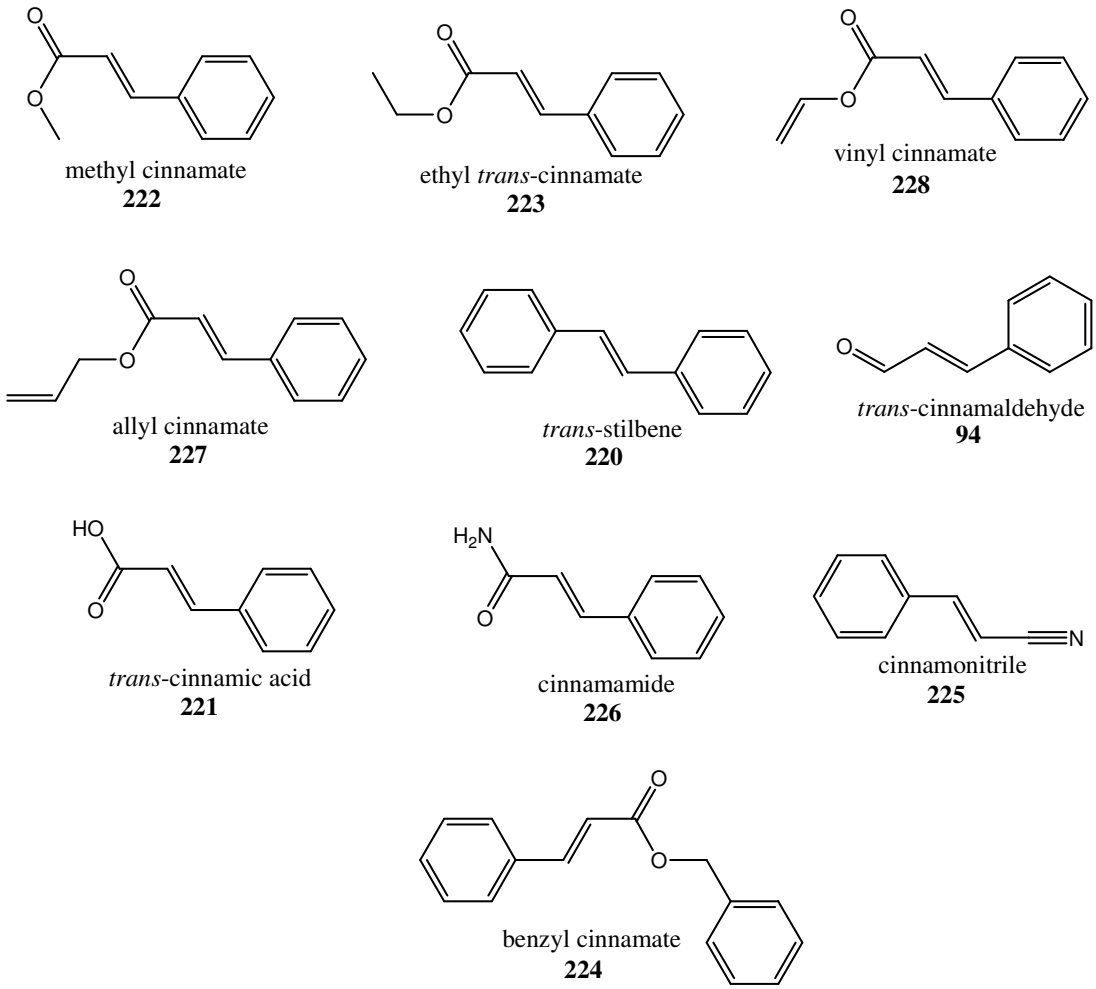


Figure 4.2 Investigated substrates in novel ILs

Trans-stilbene (**220**) was used as a test substrate to explore the applicability of the ILs as reaction solvents for hydrogenations. Hydrogenation was then carried out using a variety of cinnamic compounds with varying functional groups (aldehyde, ester, acid, amide, nitrile). Features of the ILs were investigated, together with the applicability of the ILs as solvents for recycling procedures. The percentage selectivity (Equation 1) was calculated according to the following equation:[11]

$$\%selectivity = \frac{\%product}{\sum \%products} x100$$

Equation 1 % Selectivity calculation

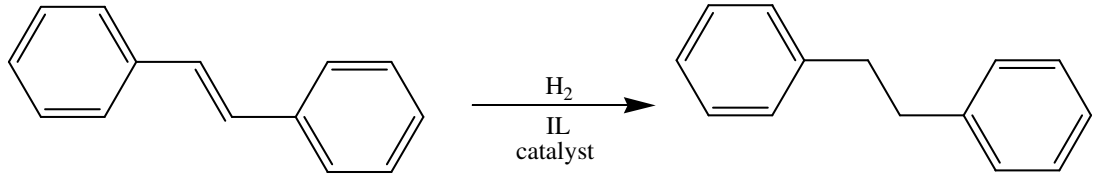
The percentage conversion (Equation 2) was calculated according to the following equation:

$$\%conversion = \frac{\sum products}{substrate + \sum products} \times 100$$

Equation 2 % Conversion calculation

4.2 *Trans*-stilbene (220)

The reduction of stilbene normally leads to one product, 1,2-diphenylethane (**229**) (Figure 4.3). Selective reduction of the double bond in *trans*-stilbene can be attributed to the fact that phenyl rings are notoriously difficult to reduce, with few exceptions.[12]



trans-stilbene
220

1,2-diphenylethane
229

Figure 4.3 Hydrogenation of *trans*-stilbene

1,2-Diphenylethane (**229**) is desirable as a derivative for its anti-estrogenic properties.[13] For hydrogenation of *trans*-stilbene in the novel ILs, 1,2-diphenylethane was the only product observed. 80 ºC was chosen as the temperature for these reactions, however 110 °C was necessary to dissolve the substrate in the [$OctOSO_3$] ILs. The elevated temperature was used to facilitate the dissolution of the solid *trans*-stilbene in the ILs. The exception to this high temperature was with the **178d** and **181d** IL. Dissolution of the substrate was observed at 55 °C in these ILs. For hydrogenations carried out in the [$OctOSO_3$] ILs, distillation under high vacuum was used to separate the product from the IL/catalyst system. Organic solvents (hexane, diethyl ether, acetonitrile, dichloromethane, chloroform, acetone, toluene, methanol, ethyl acetate, dioxane) were investigated as solvents for extraction, however all were at least partially soluble in the IL. The hydrogenation of this substrate in the ILs was examined according to various factors (IL anion, IL cation, recylability).

4.2.1 Effect of IL anion on hydrogenation

Concerning the IL of pentyl side chain, switching the anion from [NTf_2] (**178d**) to [$N(CN)_2$] (**178e**) significantly reduced the percentage conversion, from 100 to only 2 %. This drop in conversion is not noted for any of the other anions observed using the pentyl derivative (Table 4.1).

178		
Temp. (° C)	**Anion**	**Conversion (%)**
55	NTf_2 **d**	100
80	$N(CN)_2$ **e**	2
	PF_6 **c**	98
	BF_4 **b**	74
110	$OctOSO_3$ **f**	100

Table 4.1 Anion effect with **178** cation

Also, using the propoxyethoxy side chain (**181**), the [$OctOSO_3$] IL (**181f**) gave identical results to the [NTf_2] IL (**181d**) albeit at a higher temperature (Table 4.2).

181		
Anion	**Temp. (° C)**	**Conversion (%)**
NTf_2 **d**	55	100
$OctOSO_3$ **f**	110	100

Table 4.2 Anion effect with **181** cation

4.2.2 Effect of IL cation on hydrogenation

4.2.2.1 IL side-chain

Although an increase in temperature from 55 to 80 °C was necessary to facilitate dissolution of the *trans*-stilbene substrate in all [NTf_2] ILs tested apart from the pentyl (**178d**) and propoxyethoxy derivative (**181d**), the effect of the side chain did not deliver major differences in terms of conversion (Table 4.3).

NTf_2 ILs (d)		
Cation	**Temp. (° C)**	**Conversion (%)**
178	55	100
179	80	95
180	80	100
181	80	100
183	80	93
185	80	100

Table 4.3 IL side-chain effect with [NTf_2] ILs

All ILs tested for the hydrogenation of *trans*-stilbene proved successful, however the lowest conversions were observed for the cation derivatives with the side chain terminating in an ethereal methyl group.

4.2.3 Recyclability

Using **178d** the IL/catalyst system was reused 20 times with no reduction in selectivity (Table 4.4). The conversion did not fall below 100 % until the 18th recycle experiment, where the conversion was seen to drop to 93 %. Subsequent recycle experiments showed the conversion not to reach 100 % again, and thus the recycling experiment was terminated. It is noteworthy that the ^{1}H NMR of the IL showed no degradation after all recycling experiments. The IL had undergone 576 hours in total of hydrogenation reactions at 55 °C.

178d				
Experiment/ Recycle	**Conversion (%)**	**Time (h)**	**Experiment/ Recycle**	**Conversion (%) at 24 h**
E1	91	5	R8	100
	100	24	R9	100
	100	48	R10	100
R1	59	5	R11	100
	100	24	R12	100
	100	48	R13	100
R2	75	5	R14	98
	100	24	R15	100
	100	48	R16	100
R3	100	24	R17	100
R4	97	24	R18	93
R5	100	24	R19	94
R6	98	24	R20	94
R7	98	24		

Table 4.4 IL recyclability (**178d**)

Changing the cation of the IL while using the same [NTf_2] anion showed almost no effect on the recyclability up to 2 recycles. Using the [PF_6] IL (**178c**), upon the 1st recycle no difference was seen. The [BF_4] IL (**178b**) showed a significant decrease from 74 to 60 % conversion upon 1st recycle and the [$OctOSO_3$] IL (**178f**) showed the poorest result in terms of recyclability, a drop from 100 % to 0 % conversion upon the 1st recycle (Table 4.5).

Cation	Anion	Temp. (° C)	Exp./ Recycle	Conversion (%)
179	NTf_2 **d**	80	E1	98
			R1	100
			R2	98
180	NTf_2 **d**	80	E1	100
			R1	100
181	NTf_2 **d**	55	E1	100
			R1	98
183	NTf_2 **d**	80	E1	93
			R1	100
178	PF_6 **c**	80	E1	98
			R1	98
	BF_4 **b**	80	E1	74
			R1	60
	$OctOSO_3$ **f**	110	E1	100
			R1	0

Table 4.5 IL recyclability with various ILs

4.2.4 NMR analysis

The conversion of *trans*-stilbene (**220**) to 1,2-diphenylethane (**229**) can be easily monitored by the disappearance of the olefinic singlet representing two protons at ~ 7 ppm on the ^{1}H NMR spectrum. The appearance of another singlet more upfield, representing four equivalent protons at ~ 2.8 ppm appears as the double bond is hydrogenated. As can be seen from the ^{1}H NMR spectrum of the substrate and the product, the two are easily distinguishable (Figure 4.4).

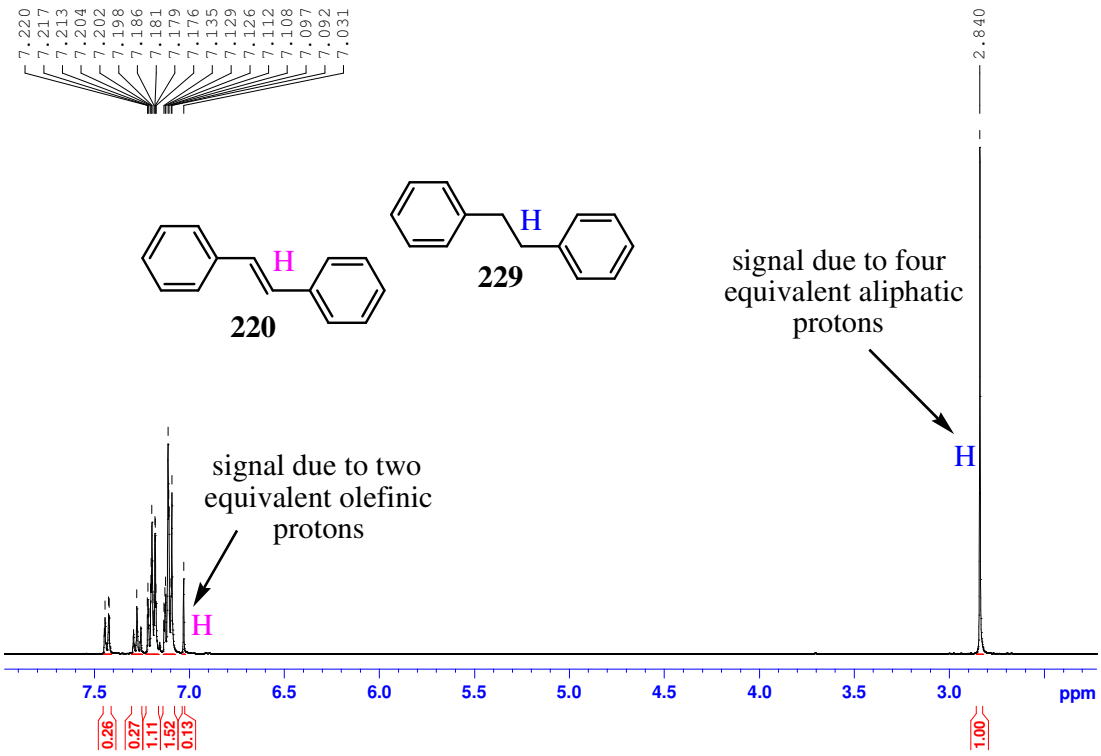


Figure 4.4 ^{1}H NMR spectrum of **220** and **229**

As the samples were monitored at 5 h and 24 h, a quick analysis by ^{1}H NMR was possible while the substrate and products remained in the IL mixture. The hydrogenation of the substrate and subsequent conversion to product can be seen amidst the proton peaks of the IL (Figure 4.5).

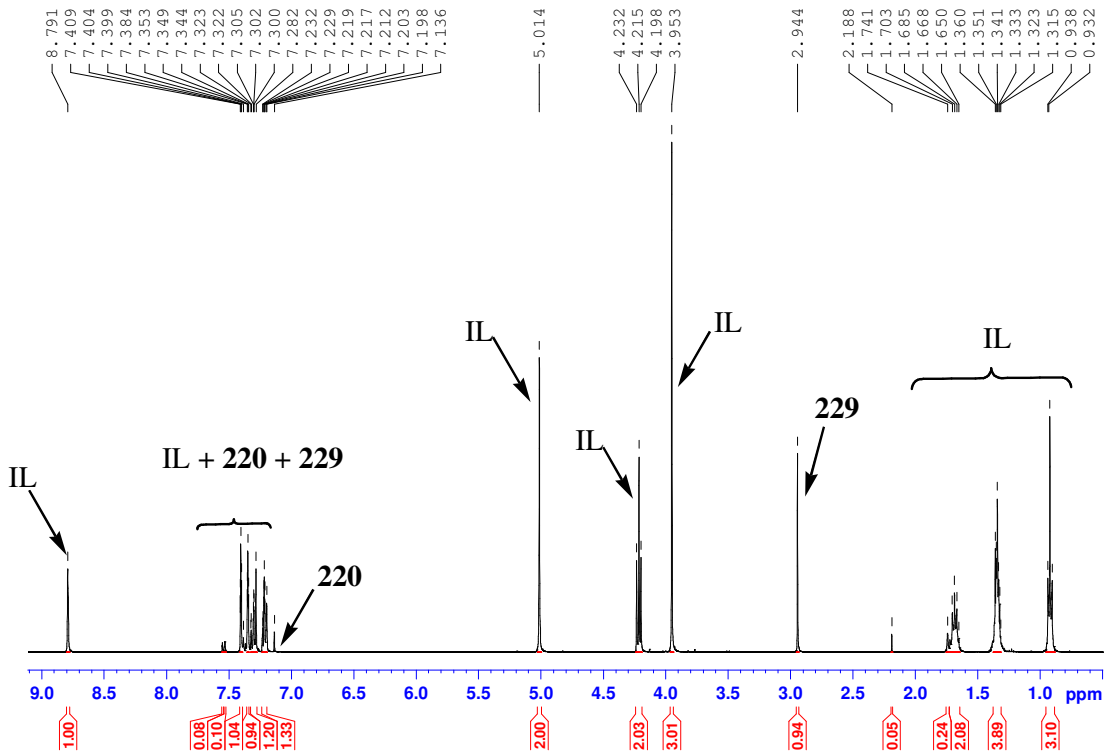


Figure 4.5 ^{1}H NMR of substrate and product in IL

4.3 *Trans*-cinnamaldehyde (94)

The α,β-unsaturated aromatic aldehyde, *trans*-cinnamaldehyde (**94**) was hydrogenated in a broad range of achiral ILs. Due to its highly conjugated system, the hydrogenation of this α,β-unsaturated aldehyde not only leads to the reduction of the olefin moiety, but also the carbonyl group, yielding 3-phenylpropanol (**97**). Three main products however may be obtained from the reduction of this substrate; the saturation of the olefinic bond leads to the saturated aldehyde, hydrocinnamaldehyde (**95**), the reduction of the carbonyl group to yield the unsaturated alcohol, cinnamyl alcohol (**96**), and the reduction of both functionalities to yield the saturated alcohol, 3-phenylpropanol (**97**) (Figure 4.6).

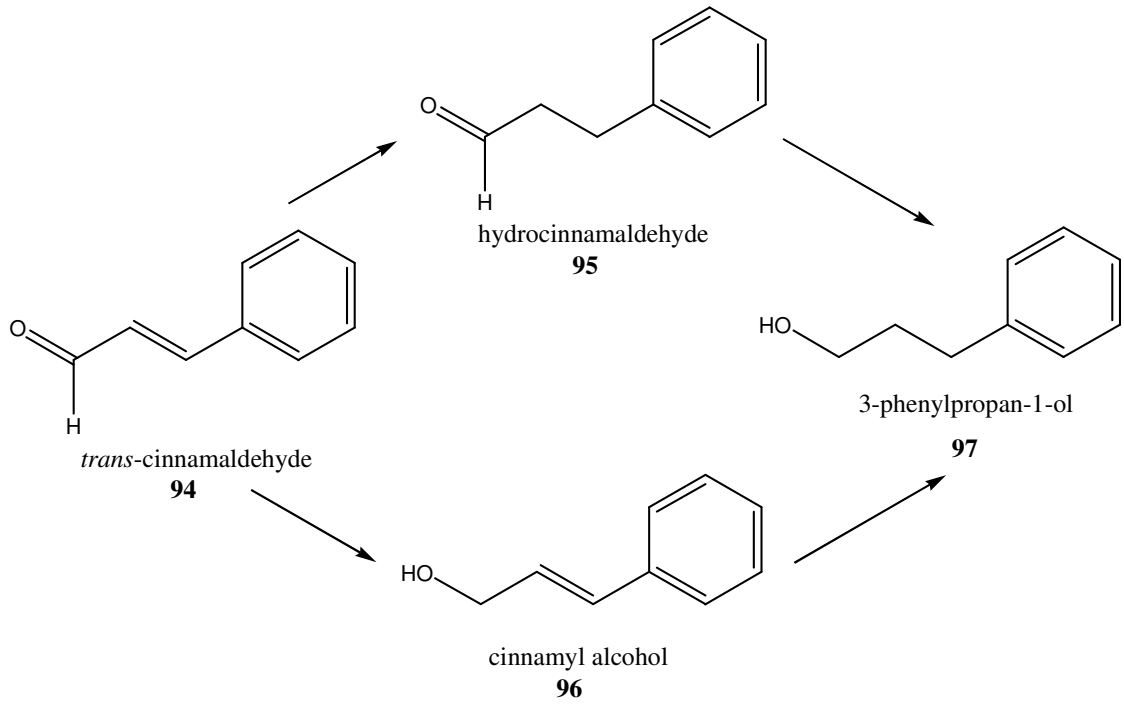


Figure 4.6 Hydrogenation of *trans*-cinnamaldehyde

As the resulting products of the hydrogenation of *trans*-cinnamaldehyde (**94**) are widely used in the fine chemical industry,[14-16] it is desirable to selectively synthesise each product. The selectivity of the reduction of this substrate varies due to the two potential reducible functionalities in the compound, namely the alkene and carbonyl moiety. Due to the thermodynamically favoured reduction of the C=C bond over the C=O bond,[17, 18] the selectivity towards the unsaturated alcohol (**96**) is generally poor. This can be frustrating as **96** is used widely in the flavouring and perfume industries. Hydrocinnamaldehyde (**95**) however also deserves merit as it has uses in the perfumery industry and also in the important field of drug synthesis of anti-HIV compounds.[19-21]

Nuithitikul and Winterbottom[22] selectively reduced the olefin moiety of cinnamaldehyde using an aqueous solution of a rhodium (I) complex (chlorotris(*meta*-trisulphonato triphenylphosphine). The reactions were carried out in a batch reactor (10 – 40 atm. H_2, 50 – 90 °C) and up to 99.9 % selectivity towards the saturated aldehyde was observed using a biphasic system (water/toluene). Reductions of cinnamaldehyde based on ruthenium catalysts were carried out by Hajek *et al.*[23] and Qiu *et al.*.[24]At 50 atm. H_2 using a 5 % Ru/Y catalyst (Y: alumosilicate zeolite used in petrochemistry), Hajek *et al.* achieved selectivity up to 70 % towards the unsaturated alcohol. Qiu *et al.* achieved similar selectivity (79.1 %), also towards the reduction of the carbonyl moiety, using a carbon nanotubes-supported Pd-Ru catalyst at 120 °C and 50 atm. H_2 pressure. Better results were obtained using the combined metal system than with each metal

alone, speculated by the group to be due to a synergic effect or a promoting effect exerted by ruthenium. Our investigations using recyclable Pd/C catalysts in ILs at 1 atm. H_2 pressure to give selective reduction of the double bond in cinnamaldehdyde represent a significant result.

Over the course of the reactions performed in the novel ILs, **96** was never observed, leading to the conclusion that the C=C double bond is reduced first, followed by the carbonyl group. The selectivity towards **95** was in every case much greater than that of 3-phenylpropanol (**97**), the latter being formed mostly in minute quantities. Due to the viscosity of the ILs, the temperature chosen initially for these reactions was 55 ºC as it was not too high to speed up the degradation of the IL, or to significantly lower the solubility of the gas in the IL. This was seen to be the optimal temperature for most reactions carried out, as the IL became less viscous therefore facilitating easier stirring and dissolution of the substrate. The hydrogenation of this substrate in the ILs was investigated according to various factors (IL anion, IL cation, IL purification, reaction temperature, catalyst used, organic solvent comparison and recycling).

4.3.1 Effect of IL anion on hydrogenation

The most impressive results were achieved using the [NTf_2] ILs, in comparison with the other four anions studied (Table 4.6).

	178	
Anion	**Conversion (%)**	**Selectivity (%)**
NTf_2 **d**	98	94
BF_4 **b**	0	-
$N(CN)_2$ **e**	12	100
$OctOSO_3$ **f**	25	100

Table 4.6 Anion effect with **178** cation

It was seen here that the [NTf_2] salt (**178d**) gave a far superior result in terms of conversion and selectivity in comparison to the ILs of differing anions.

The [NTf_2] IL (**181d**) was again shown to give superior results in comparison with the [PF_6] anion of the same IL (**181c**). This time a cation containing an oxygen atom was used as comparison for the two ILs (Table 4.7).

181		
Anion	**Conversion (%)**	**Selectivity (%)**
NTf_2 **d**	100	93
PF_6 **c**	77	100
$N(CN)_2$ **e**	5	100
BF_4 **b**	15	88
$OctOSO_3$ **f**	2	100

Table 4.7 Anion effect with **181** cation

Although 100 % selectivity was reached using the [PF_6] analogue (**181c**), a compromise in conversion was observed (77 %). Therefore the [NTf_2] IL (**181d**) is shown to be the superior IL, reaching 100 % conversion and 93 % selectivity within 48 hours.

Once again, choosing a different cation (**186**), in comparison to the [BF_4] analogue of the IL (**186b**), the [NTf_2] IL (**186d**) shows superior results, albeit negligible. The result obtained with the **186d** shows minimal conversion (Table 4.8).

186		
Anion	**Conversion (%)**	**Selectivity (%)**
NTf_2 **d**	5	100
BF_4 **b**	0	0

Table 4.8 Anion effect with **186** cation

Overall, for all the ILs tested, the [$N(CN)_2$] and [BF_4] displayed the lowest percentage conversions. The [$OctOSO_3$], although displaying poor activity in the second case, showed modest conversion in the case of the pentyl side-chain IL (**178f**). One [PF_6] IL (**169e**) showed promising activity in comparison with the other IL anions.

4.3.2 Effect of IL cation on hydrogenation

4.3.2.1 Effect of side-chain

Regarding side chain lengths and the number of ethereal oxygen atoms in the side chain, the number of oxygens seems to play a less significant role than the length of the terminal alkyl chain (Table 4.9).

NTf_2 IL (d)		
Cation	**Conversion (%)**	**Selectivity (%)**
178	98	94
181	98	74
182	13	100
183	5	100
185	97	88
186	5	100

Table 4.9 Side-chain effect with [NTf_2] ILs

In the case of the [NTf_2] IL terminating with a propyl chain (**181d** and **185d**), the results for hydrogenation increased dramatically in comparison with those of either a butyl or methyl terminating chain.

Comparing differing side chains of the [$N(CN)_2$] anion, little difference is observed, a slight decrease in conversion is observed with the addition of an oxygen atom to the side chain (Table 4.10).

$N(CN)_2$ ILs (e)		
Cation	**Conversion (%)**	**Selectivity (%)**
178	12	100
181	5	100

Table 4.10 Side-chain effect with [$N(CN)_2$] ILs

In the case of the [$OctOSO_3$] anion, a more marked difference can be seen, with acceptable conversion being obtained with the pentyl derivative (**178f**), but the addition of the oxygen to the side chain (**181f**) seeming to inhibit conversion altogether (Table 4.11).

$OctOSO_3$ ILs (f)		
Cation	**Conversion (%)**	**Selectivity (%)**
178	25	100
181	2	100

Table 4.11 Side-chain effect with [$OctOSO_3$] ILs

4.3.2.2 Imidazolium moiety

The incorporation of a methyl group to the C_2 position of the imidazolium moiety decreased product conversion by just over 50 % (Table 4.12). What was fascinating however in this particular case was that upon the 1st recycle of the IL/catalyst system, the conversion rose from a mere 36 % after 48 hours, to an impressive 100 %, thus suggesting that perhaps pre-treatement of the IL/catalyst system with hydrogen could prove beneficial for conversion results.

NTf_2 ILs (d)		
Cation	**Conversion (%)**	**Selectivity (%)**
178	98	94
189	36	100

Table 4.12 1-methylimidazolium in comparison with 1,2-dimethylimidazolium moiety

4.3.3 Effect of IL purification on hydrogenation

4.3.3.1 Halide removal

Table 4.13 displays the results from the effect of residual halide present in the IL. It can be seen that only a slight increase in conversion is evident when residual halide is removed from the IL.

181b			
Halide ($AgNO_3$ test)	**Exp. /Recycle**	**Conversion (%)**	**Selectivity (%)**
Positive	E1	15	88
Negative	E1	24	90
	R1	32	92
	R2	16	84

Table 4.13 Halide removal (**181b**)

4.3.4 Effect of reaction temperature on hydrogenation

In the following table (Table 4.14) eight experiments using four ILs are displayed, one carried out at RT, the others at 55 °C.

NTf_2 ILs (d)			
Cation	**Temp. (° C)**	**Conversion (%)**	**Selectivity (%)**
178	RT	100	67
	55	98	94
181	RT	44	100
	55	98	74
182	RT	14	82
	55	13	100
186	RT	4	100
	55	5	100

Table 4.14 Reaction temperature effect using [NTf_2] ILs

For the first two examples with ILs **178d** and **181d**, the increase in temperature from RT to 55 °C exerts a positive effect on the results obtained. Although in the case of **181d**, the selectivity decreases with temperature, the increase in conversion from 44 – 100 % compensates for the small drop in selectivity. For ILs **182d** and **186d**, terminating with the butyl chain, the conversion is poor, and even when the temperature is increased, no significant increase in conversion can be viewed.

4.3.5 Effect of catalyst used on hydrogenation

The comparison of different palladium loadings (5 and 10 %) and the effect of switching from palladium to platinum catalyst are shown in Table 4.15. It is evident that the 10 % Pd/C (**92**) catalyst achieved a significantly increased conversion in comparison with its 5 % Pd/C (**92**) counterpart. The use of platinum on carbon (**91**) as a catalyst for this system is shown to be poorly active with a very low conversion rate being achieved.

181d		
Catalyst	**Conversion (%)**	**Selectivity (%)**
10% **92**	100	93
5% **92**	91	74
91	19	87

Table 4.15 Varying catalysts with **181d**

4.3.6 Comparison of novel ILs with organic solvent and conventional ILs

The best results in terms of both conversion and selectivity obtained using the novel ILs were compared with results obtained using conventional ILs and an organic solvent (Table 4.16). Although 100 % conversion was reached with the conventional ILs and organic solvent, 100 % selectivity was only obtained using the novel ILs.

Cation	Exp./ Recycle	Temp. (° C)	Time (h)	Conversion (%)	Selectivity (%)
[bmim][NTf_2] **107**	E1	55	24	100	87
[bmim][$OctOSO_3$] **230**	E1	55	24	100	69
Toluene	E1	RT	24	100	67
185d	R1	55	5	35	100
			24	100	100
			48	100	88
189d	R1	55	5	21	100
			24	100	100
			48	100	93

Table 4.16 ILs/organic solvent/conventional ILs hydrogenation comparison

After 24h, it can be seen that the novel ILs (**185d** and **189d**) can display superior results to conventional ILs (**107** and **230**) or conventional organic solvents (toluene). 100 % conversion and selectivity were obtained upon the first recycle of two novel ILs after 24h.

4.3.7 Effect of recycling on hydrogenation

IL **181d** was recycled as reaction solvent 16 times (Table 4.17).

181d							
Exp./ Recycle	**Time (h)**	**Conversion (%)**	**Selectivity (%)**	**Exp./ Recycle**	**Time (h)**	**Conversion (%)**	**Selectivity (%)**
E1	5	9	100	R9	5	-	-
	24	65	100		24	-	-
	48	100	93		48	48	79
R1	5	9	100	R10	5	-	-
	24	22	100		24	-	-
	48	48	80		48	59	83
R2	5	3	100	R11	5	-	-
	24	8	100		24	-	-
	48	30	56		48	19	78
R3	5	7	100	R12	5	-	-
	24	8	100		24	-	-
	48	28	79		48	12	79
R4	5	-	-	R13	5	-	-
	24	-	-		24	-	-
	48	56	80		48	15	78
R5	5	9	100	R14	5	-	-
	24	20	100		24	-	-
	48	66	79		48	24	84
R6	5	-	-	R15	5	-	-
	24	-	-		24	-	-
	48	23	80		48	13	67
R7	5	-	-	R16	5	-	-
	24	-	-		24	-	-
	48	63	77		48	20	72
R8	5	13	80				
	24	28	45				
	48	55	80				

Table 4.17 Recycling of **181d**

Samples were not taken at 5 and 25 hour intervals for each recycle procedure due to the small scale of the reaction and therefore the diminishing quantity of IL. It is evident from the results that the first reaction proved to be the most successful, with a dramatic reduction in conversion of product for the next reaction and indeed all following reactions (Figure 4.7). Something to note is the percentage conversion of the main product formed for the first 3 recycles and the subsequent increase upon recycle number 4 and 5. This result may suggest that pre-treatment of the IL/catalyst system with H_2 may be beneficial for this particular system. Also worth noting is the fact that, even with the widely varying percentage conversion, the selectivity remains almost constant over the whole recycling procedure, never falling below 56 % (Figure 4.7).

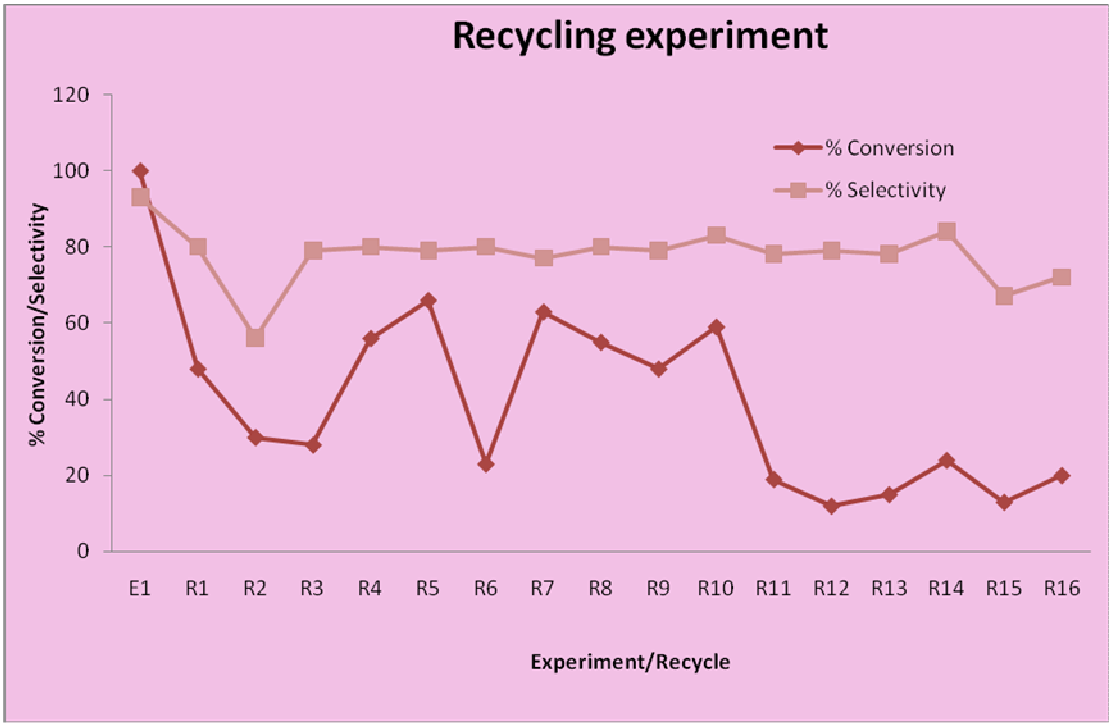


Figure 4.7 Recycling of **181d**

What is interesting to note is that, not all the best results were obtained on the first run, but on the second run (R1), thus suggesting in some cases the need for an initiating period for the catalyst with hydrogen and substrate for optimizing the conversion and selectivity (Table 4.18). One particular example is the case of the hydrogenation carried out in **189d**. The conversion more than doubles upon recycling in Run 1 from 36 % to 100 %. Optimum conversion and selectivity are thus observed on this run. For subsequent runs however after run 1, the conversion after 48 hours varies from 97 – 100%.

189d			
Exp./Recycle	**Time (h)**	**Conversion (%)**	**Selectivity (%)**
E1	5	2	100
	24	8	100
	48	36	100
R1	5	21	100
	24	100	100
	48	100	93
R2	5	19	100
	24	48	73
	48	97	98
R3	5	21	100
	24	79	99
	48	100	96
R4	5	22	100
	24	89	100
	48	97	100

Table 4.18 Recycling of **189d**

Another example of substrate recycling can be seen in Table 4.19 using IL **185d**. An increased conversion was achieved upon recycling on R1, from 32 % to 100 %, and then decreased from 100 % in increments of 15 % and 19 % respectively.

185d			
Exp./Recycle	**Time(h)**	**Conversion (%)**	**Selectivity (%)**
E1	5	9	100
	24	32	100
	48	97	88
R1	5	35	100
	24	100	100
	48	100	88
R2	5	10	100
	24	31	100
	48	85	91
R3	5	9	100
	24	34	90
	48	64	93

Table 4.19 Recycling of **185d**

Using the [BF_4] IL (**181b**) which had been washed with water in order to remove excess halide, the conversion, albeit low (24 %) upon the first experiment, increased upon recycle 1 to 32 %. It decreased however again upon the subsequent recycle (Table 4.20).

181b		
Exp./ Recycle	**Conversion (%)**	**Selectivity (%)**
E1	24	90
R1	32	92
R2	16	84

Table 4.20 Recycling of **181b**

Using the [PF_6] IL (**181c**) a reduction in conversion was noted upon the first recycle. The selectivity however was not negatively affected, remaining at 100 % throughout the recycling procedure (Table 4.21).

181c			
Exp./Recycle	**Time (h)**	**Conversion (%)**	**Selectivity (%)**
E1	5	4	100
	24	32	100
	48	77	100
R1	48	58	100

Table 4.21 Recycling of **169e**

4.3.8 NMR analysis

Crude products were extracted from the respective ILs (distilled in the case of the [$OctOSO_3$] ILs) and analysed by ^1H NMR (Figure 4.8). Where there was still unreduced substrate, the olefinic doublet of doublets at ~ 6.7 ppm was integrated to one, therefore equal to one proton signal. As the hydrocinnamaldehyde was formed, the aldehydic triplet at ~ 9.8 ppm due also to 1 proton, allowed for the ratio of the substrate and this product to be evaluated. The aliphatic triplet, the signal due to the methylene protons adjacent to the hydroxyl group, at ~3.6 ppm was taken as a reference peak for the formation of 3-phenylpropanol. However, as this signal was due to 2 protons, the value of its integration was halved to allow for correct calculation of product ratios.

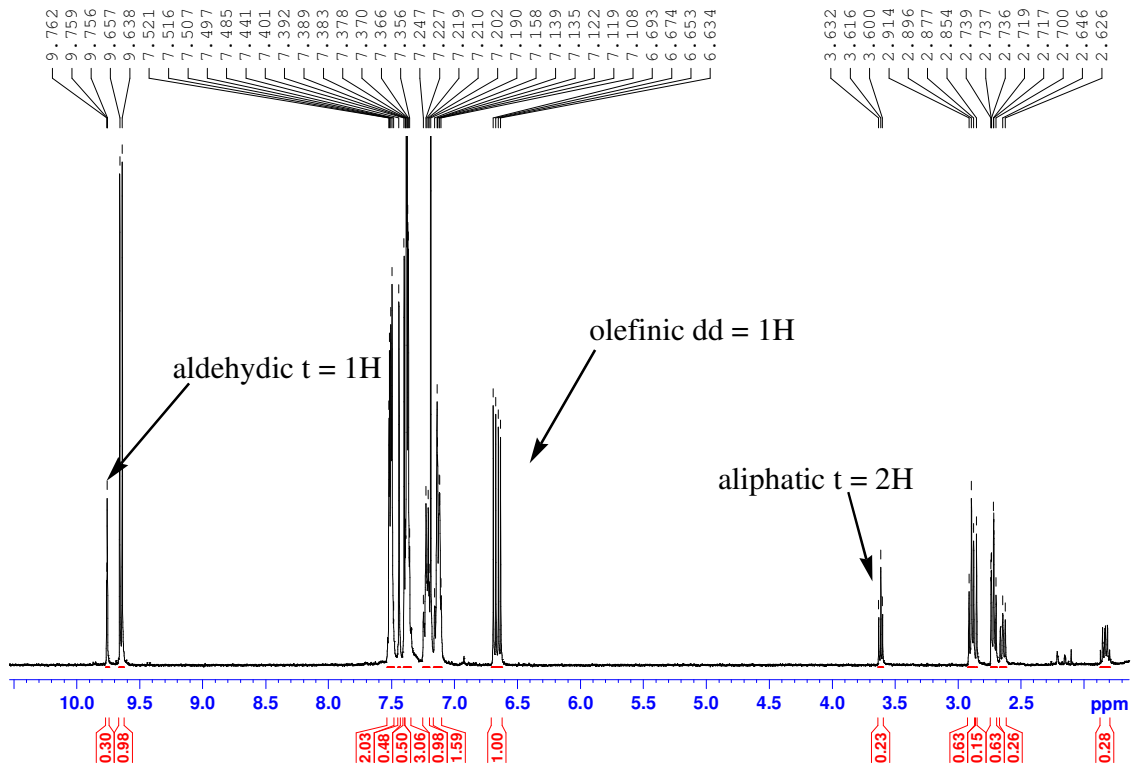


Figure 4.8 Crude product

It was also proven that the identification and rough quantitation of the products could be obtained while still in the IL, as shown in the ^{1}H NMR spectrum (Figure 4.9).

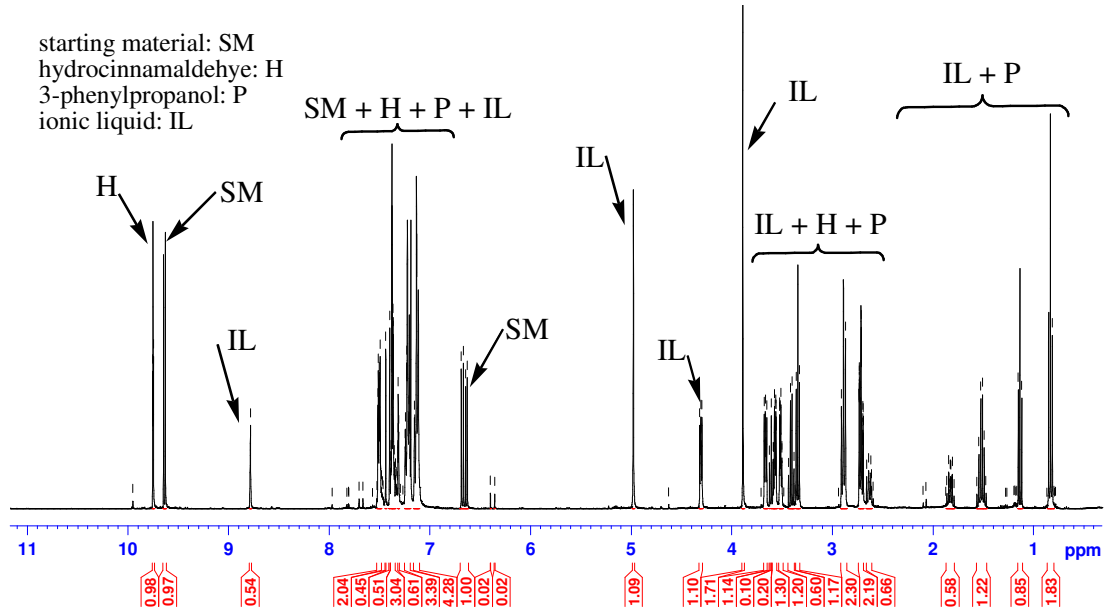


Figure 4.9 Crude product in IL

Even while still present in the IL, a peak for each of the products and the starting material can be identified and subsequently used to determine the ratio of starting material to products.

Impressive selectivity may be observed from the ^{1}H NMR spectrum (Figure 4.10), showing a 24h sample taken before all the starting material had been converted to product. Although 100 % conversion was not yet reached, 100 % selectivity is observed.

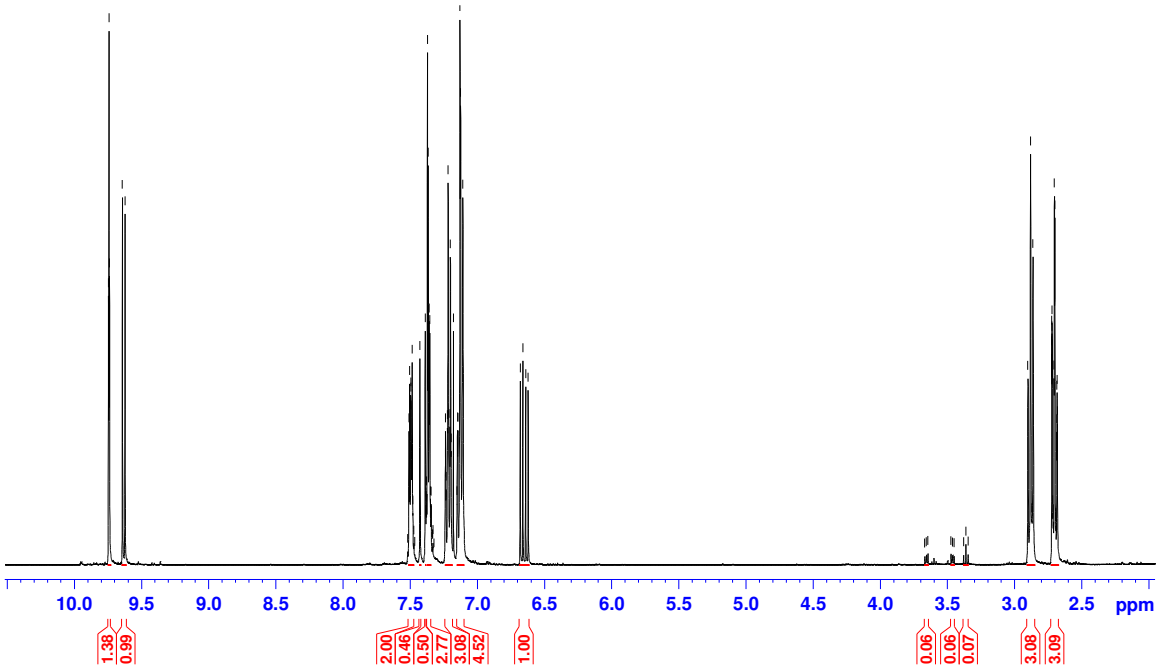


Figure 4.10 ^{1}H NMR displaying selectivity to hydrocinnamaldehyde (**95**)

In order to confirm that the integration of the NMR peaks correlated to the obtained isolated yields, ^{1}H NMR peak ratios were in some cases confirmed by crude product extraction followed by column chromatography separation and subsequent calculation of isolated yield. Hydrocinnamaldehyde (**95**) was successfully separated from 3-phenylpropanol (**97**) using column chromatography with a mobile phase of 30:70 ethyl acetate:hexane. For correct separation and correct calculation of product ratios, the column must be prepared and run immediately following termination of the reaction. It was noted that, as the crude product was allowed to stand in air, hydrocinnamaldehyde (**95**) was oxidised to hydrocinnamic acid (**231**). Although of inconvenience for correct calculation of isolated yield in these circumstances, oxidation of 3-phenylpropanol (**97**) is beneficial as an alternate route towards the synthesis of 3-phenylpropionic acid (**231**). In their patent, Castelijns *et al.* [25]describe a similar route for the synthesis of this acid, covering the selective hydrogenation of cinnamaldehyde (**94**) to 3-phenylpropanal (**95**) followed by the subsequent oxidation of this intermediate to 3-phenylpropionic acid (**231**). Formation of this oxidised product occurred readily, even when hydrocinnamaldehyde (**95**) was stored in a sealed container. Three NMR samples were

taken to show the oxidation of the product, the 1st directly after the product was eluted from the column, the 2nd after storage in a sealed sample vial over 18h, and the 3rd after storage in the same vial after 20 h (Figure 4.11).

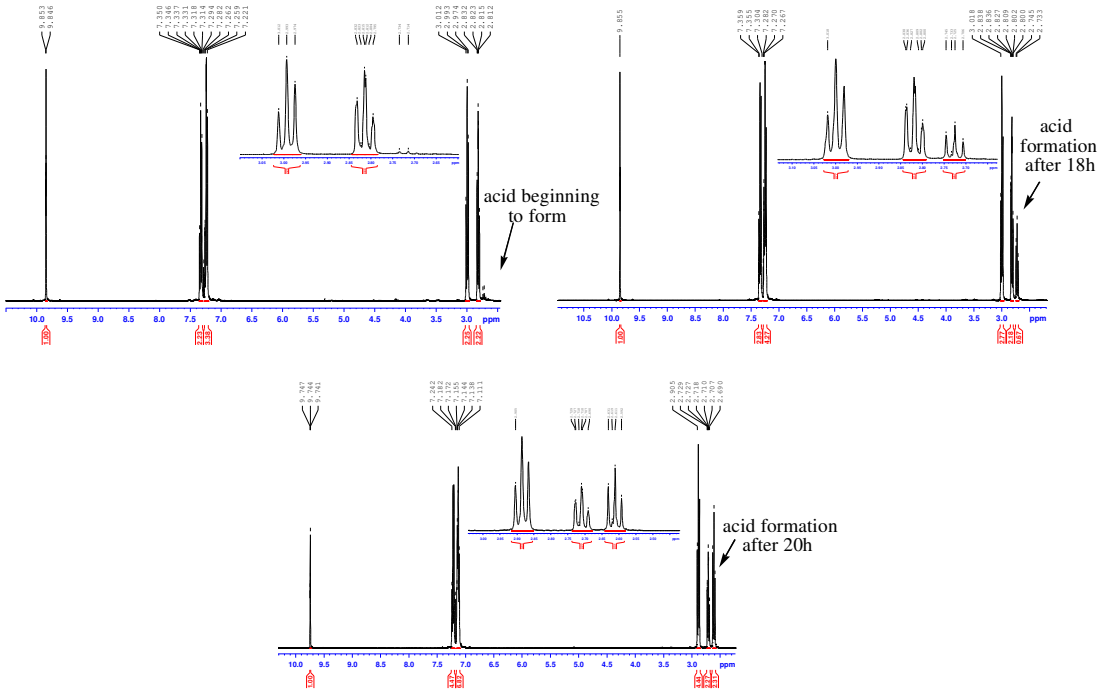
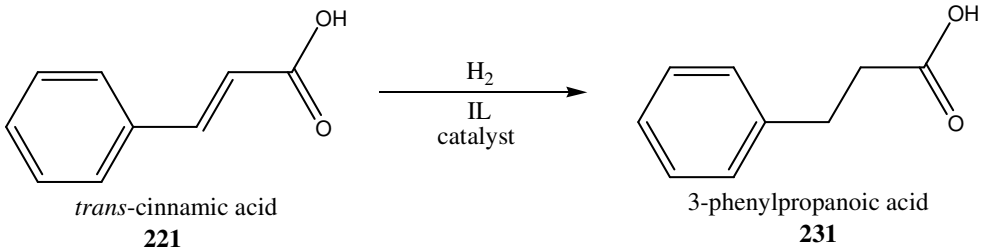


Figure 4.11 ^{1}H NMR spectra of **95** showing development of product **231**

After 20h an almost exact 50:50 ratio of hydrocinnamaldehyde (**95**) to hydrocinnamic acid (**231**) can be observed. Because of this oxidation process, in order to successfully quantify the amount of hydrocinnamaldehyde present, the column was always performed directly upon termination of the reaction.

4.4 *Trans*-cinnamic acid (221)

The hydrogenation of *trans*-cinnamic acid in the novel ILs resulted in formation of a single product, 3-phenylpropanoic acid (**231**) (Figure 4.12).



trans-cinnamic acid
221

3-phenylpropanoic acid
231

Figure 4.12 Hydrogenation of *trans*-cinnamic acid

The hydrogenation of *trans*-cinnamic acid (**221**) in the novel ILs was examined according to the following factors: IL anion, IL cation, IL purification and recyclability.

4.4.1 Effect of IL anion on hydrogenation

With the pentyl side chain ILs and differing anions, the [$OctOSO_3$] IL (**178f**) shows the poorest conversion, with only 76 % being reached after 48 h in comparison with 100 % for the [NTf_2] (**178d**) and [PF_6] (**178c**) derivatives (Table 4.22).

178		
Anion	**Time (h)**	**Conversion (%)**
NTf_2 **d**	48	100
PF_6 **c**	48	100
$OctOSO_3$ **f**	48	76

Table 4.22 Anion effect with **178** cation

However, regarding **181f**, no compromise in conversion is evident using this IL in comparison with the [NTf_2] derivative (**181d**). When the side chain length is increased to the propoxyethoxyethoxy derivative (**185d** and **185f**), this statement also holds true (Table 4.23).

Conversion = 100 %	
Cation	**Anion**
181	NTf_2 **d**
	$OctOSO_3$ **f**
185	NTf_2 **d**
	$OctOSO_3$ **f**

Table 4.23 Anion effect

4.4.2 Effect of IL cation on hydrogenation

4.4.2.1 Side-chain effect

All side chains of the [NTf_2] ILs tested were consistent with the double bond of cinnamic being hydrogenated within a 48 h period (Table 4.24).

NTf_2 IL (d) Conversion = 100 %
178
179
181
182
185

Table 4.24 Side-chain effect with [NTf_2] ILs

4.4.2.2 Imidazolium moiety

No difference can be seen in terms of conversion after 48 hours when the 1,2-dimethylimidazolium derivative is used (Table 4.25).

NTf_2 IL (d) Conversion = 100%
178
189

Table 4.25 ILs of 1-methylimidazolium and 1,2-dimethylimidazolium moiety

4.4.3 Effect of IL purification on hydrogenation

4.4.3.1 Colour removal

Removal of colour from the **189d** showed no difference in terms of conversion obtained after 48 hours (Table 4.26).

NTf_2 ILs (d) Conversion = 100 %	
Cation	**Appearance**
189	Yellow solid
	Colourless solid

Table 4.26 Colour effect (**189d**)

The same effect was noted with the [PF_6] derivative of the IL (**189c**) (Table 4.27).

PF_6 ILs (c) Conversion = 100 %	
Cation	**Appearance**
189	Yellow solid
	Colourless oil

Table 4.27 Colour effect (**189c**)

4.4.4 Effect of recycling on hydrogenation

The IL/catalyst system was successfully recycled for the hydrogenation of *trans*-cinnamic acid (**221**) with no decrease in conversion obtained after 48 hours (Table 4.28).

Conversion = 100%		
Solvent	**Anion**	**Exp./ Recycle**
178	PF_6 **c**	E1
		R1
		R2
189 (colourless)	NTf_2 **d**	E1
		R1
185	NTf_2 **d**	E1
		R1

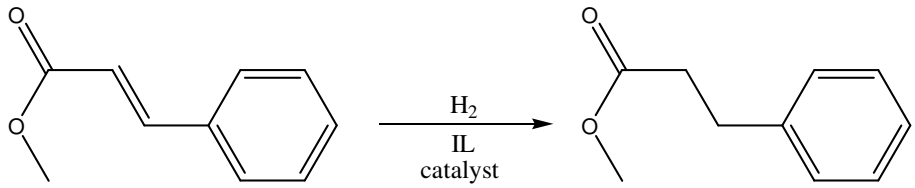
Table 4.28 Recycling effect

For the reactions carried out in the [$OctOSO_3$] ILs (**f**), vacuum distillation was not a viable method for separation of the product from the IL/catalyst mixture, as the boiling point was too high > 200 °C. In order to separate the product from the [$OctOSO_3$] mixture, the mixture was filtered through a short plug of silica, the first spot eluting with 100 % DCM being the desired product.

4.5 Cinnamate esters

4.5.1 Methyl cinnamate (222)

Methyl cinnamate was selectively reduced to methyl 3-phenylpropanoate (**232**) (Figure 4.13). Only one product was observed, that of methyl 3-phenylpropanoate (**232**).



methyl cinnamate
222

methyl 3-phenylpropanoate
232

Figure 4.13 Hydrogenation of methyl cinnamate

Most hydrogenations carried out with methyl cinnamate (**222**) were found to have reached 100 % conversion by 24 h, therefore none were left any longer than this time. The temperature was increased from 55 to 80 °C for the [$OctOSO_3$] hydrogenations in order to facilitate solubility of the substrate in the IL. The factors investigated while using this substrate included: IL anion, IL cation, purification and recyclability.

4.5.1.1 Effect of anion on hydrogenation

Changing the anion did not effect the conversion. Again, the only decrease in conversion from 100 % was observed when the [$OctOSO_3$] derivative (**178f**) (Table 4.29).

Cation	Anion	Exp./ Recycle	Time (h)	Temp. (° C)	Conversion (%)
178	NTf_2 **d**	E1	24	55	100
	PF_6 **c**	E1	24	55	100
	BF_4 **b**	R1	24	55	100
	$OctOSO_3$ **f**	E1	48	80	91
185	PF_6 **c**	E1	24	55	100
	$OctOSO_3$ **f**	E1	48	80	100

Table 4.29 Anion effect

4.5.1.2 Effect of IL cation on hydrogenation

4.5.1.2.1 Side-chain effect

It can be seen from the results obtained that the side chain did not affect the conversion from substrate to product concerning the [NTf_2] and [PF_6] ILs. In the case of the [$OctOSO_3$] salt however, a modification in the side chain, notably the presence of extra oxygen atoms, resulted in a rise in conversion from 91 % to 100 %. 100 % conversion was obtained with all ILs tested except for **178f** which gave a percentage conversion of 91 % (Table 4.30).

Conversion = 100 %		
Conditions	**Cation**	**Anion**
24 h, 55 °C	**178, 181, 180, 82, 183**	**d**
24 h, 55 °C	**178, 185**	**c**
48 h, 80 °C	**185, 181**	**f**

Table 4.30 Side-chain effect

4.5.1.3 Effect of IL purification on hydrogenation

4.5.1.3.1 Colour removal

The colour was initially removed from the bromide salt (**178a**), and then colourless **178a** was reacted with KPF_6 to give a colourless [PF_6] IL (**178c**). The colour of the IL did not affect the conversion of methyl cinnamate (**222**). 100 % conversion was obtained with the coloured and colourless version of **178c**.

4.5.1.4 Effect of IL recycling on hydrogenation

Three [NTf_2] ILs (**181d**, **182d** and **183d**) with varying cations were recycled once, none showing any decrease in activity upon recycling.

4.5.1.5 NMR analysis

For the hydrogenations in [$OctOSO_3$] ILs, it could be seen from the ^1H NMR of the extracted product that the anion of the IL had degraded to 1-octanol. A simple column of mobile phase ethyl acetate: hexane (30:70) separated this unwanted impurity from the desired product, the desired reduced product eluting first from the column. Due to the distillation of the product from the IL at high temperature (~ 200 °C), a hydrolysis

product from cleavage of the ester moiety was also observed in the distillate. This was also separated from the desired product.

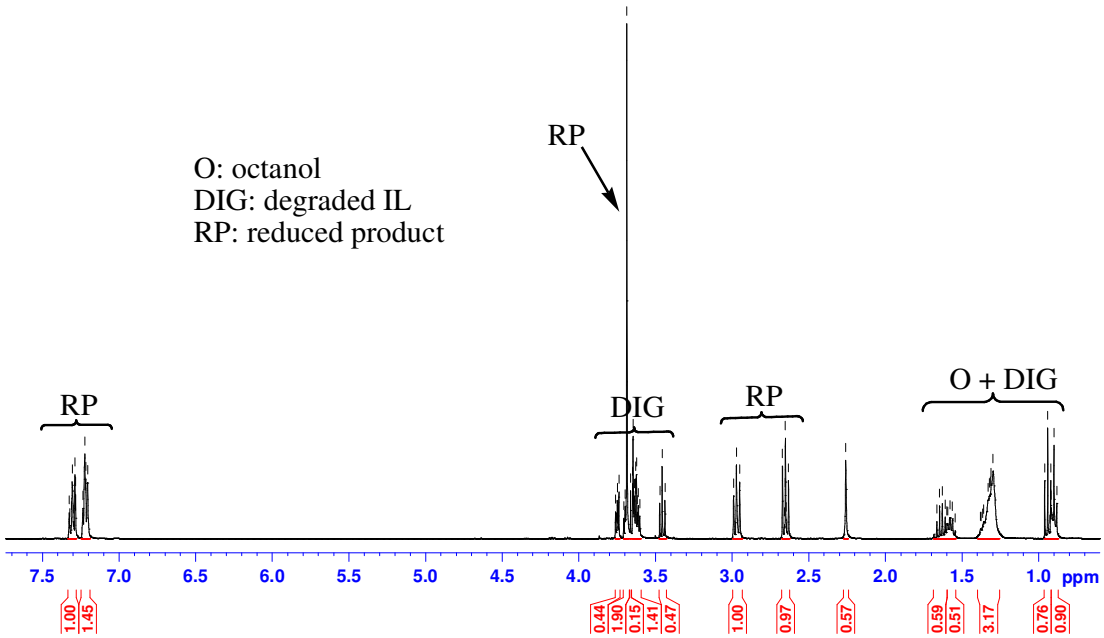


Figure 4.14 ^{1}H NMR spectrum of extract from hydrogenation in [$OctOSO_3$] IL

4.5.2 Ethyl *trans*-cinnamate (223)

Ethyl *trans*-cinnamate was reduced selectively to the diydrocinnamic ester, ethyl 3-phenyl propanoate (**233**) (Figure 4.15).

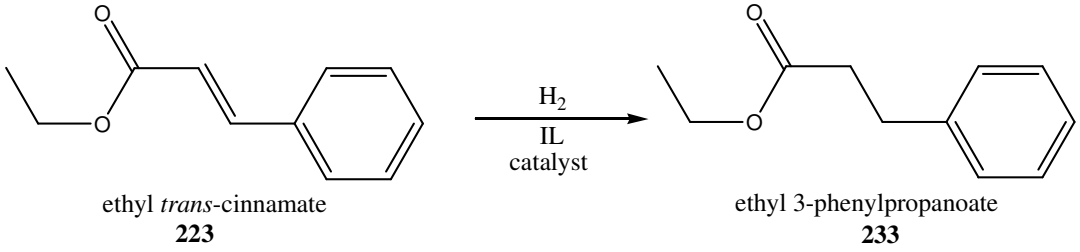


Figure 4.15 Hydrogenation of ethyl *trans*-cinnamate

All reactions using ethyl *trans*-cinnamate (**223**) as the substrate showed 100 % conversion to **233** within 24h. All reactions including the [$OctOSO_3$] IL hydrogenations were run at 55 °C. The factors affecting hydrogenation in the novel ILs investigated included: IL anion, IL cation, purification and recyclability.

4.5.2.1 Effect of IL anion on hydrogenation

For the pentyl side chain of ILs (**178**) of various anions, both the [NTf_2] and [PF_6] derivatives gave 100 % conversion after just 5 h. The [BF_4] and [$OctOSO_3$] ILs of the

same side chain however were not complete, requiring more than 5 h to reach 100 % conversion; both however were successfully reduced upon 24 h (Table 4.31).

178		
Anion	**Conversion (%)**	**Time (h)**
BF_4 **b**	50	5
	100	24
PF_6 **c**	100	5
$OctOSO_3$ **f**	100	24
NTf_2 **d**	100	5

Table 4.31 Anion effect with **178** cation

For the IL of longer side chain (**185d**), more than 5 hours was necessary but less than 24 h for the total conversion of the substrate with [PF_6] and the [$OctOSO_3$] anion. 100 % conversion was achieved using **185c** and **185f**.

4.5.2.2 Effect of IL cation on hydrogenation

4.5.2.2.1 Side-chain length

All tested [NTf_2] ILs differing only in side chain length showed 100 % conversion after 5 hours. It was in the case of ILs terminating with a butyl group that didn't reach 100 % conversion after 5 h. Indeed in these cases, 100 % was reached upon 24 h (Table 4.32).

NTf_2 ILs (d)		
Cation	Time	Conversion
179	5	100
	24	100
178	5	100
	24	100
180	5	100
	24	100
181	5	100
	24	100
182	5	86
	24	100
183	5	100
	24	100
184	5	100
	24	100
186	5	83
	24	100

Table 4.32 Side-chain effect with [NTf_2] ILs

Using the [$OctOSO_3$] ILs, upon increasing the length of the side chain or the number of oxygen atoms in the side chain, 100 % conversion was reached in all cases (**178f**, **181f** and **185f**) after 24h.

In the case of the [PF_6] ILs, increasing the side chain length meant an increase in the amount of time required to reach 100 % conversion (Table 4.33).

PF_6 ILs (c)		
Cation	**Time**	**Conversion**
178	5	100
185	5	55
	24	100

Table 4.33 Side-chain effect with [PF_6] ILs

4.5.2.2.2 Imidazolium moiety

The dimethyl imidazolium derivative (**189d**) showed a decrease in conversion in comparison to the methyl imidazolium IL (**178d**) after 5 h. **188d** does however show reaction completion with 100 % conversion reached within 24 h (Table 4.34).

NTf_2 ILs (d)		
Cation	**Time (h)**	**Conversion (%)**
178	5	100
189	5	91
	24	100

Table 4.34 Imidazolium substitution effect

4.5.2.3 Effect of IL purification on hydrogenation

4.5.2.3.1 Colour removal

The removal of colour from the IL is shown in this case to have a beneficial effect in terms of conversion (Table 4.35). After 5 hours using the colourless **189d**, 100 % conversion was reached, however after the same period of time in the coloured IL, only 91 % conversion was reached.

NTf_2 ILs (d)			
Solvent	**Appearance**	**Time (h)**	**Conversion (%)**
189	Dark yellow	5	91
		24	100
		48	100
	Pale yellow	5	100
		24	100
		48	100

Table 4.35 Colour effect with [NTf_2] ILs

4.5.2.4 Effect of IL recycling on hydrogenation

The **179d** IL system was successfully recycled five times with no loss in 100 % conversion after 24 h.

4.5.2.5 NMR Ananlysis

Product ratios were obtained from ^{1}H NMR spectra. The two distinct NMR signals of the substrate and product facilitated the calculation of starting material to product ratios from the crude ^{1}H NMR. The two olefinic doublet signals at ~ 6.4 ppm and ~ 7.6 ppm are clearly separated from the signals of the hydrogenated product. The ethyl ester signals of both products are also clearly separate from each other (Figure 4.16).

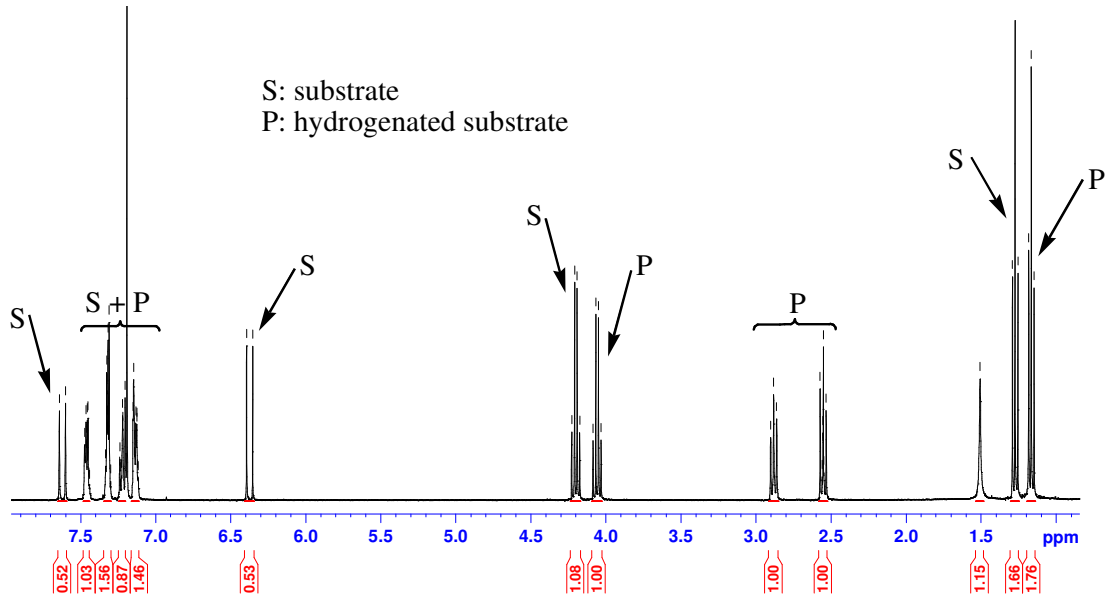
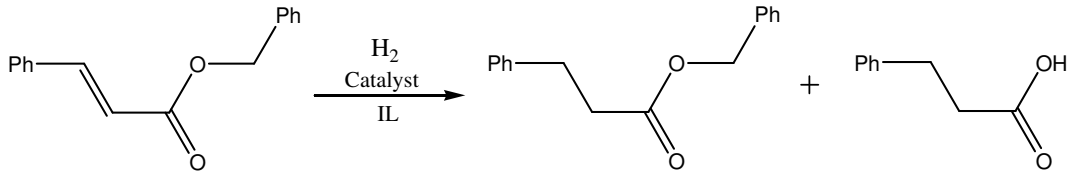


Figure 4.16 ^{1}H NMR spectrum

4.6 Benzyl cinnamate (224) – Hydrogenation v hydrogenolysis

In order to achieve the selective hydrogenation of the olefin moiety of benzyl cinnamate without hydrogenolysis of the benzyl ester, elaborate conditions are often required.[26-30]



benzyl cinnamate
224

benzyl 3-phenylpropanoate
234

3-phenylpropanoic acid
231

Figure 4.17 Hydrogenation of benzyl cinnamate

For the hydrogenation reactions carried out in the [$OctOSO_3$] ILs, vacuum distillation was not a viable method for separation of the product from the IL/catalyst mixture due to the high boiling point of the product > 200 °C. The mixture was therefore filtered through a short silica plug to separate the products from the mixture. When a mixture of

products, namely benzyl 3-phenylpropanoate (**234**) and 3-phenylpropanoic acid (**231**), were obtained, column chromatography (ethyl acetate: hexane, 4:1) was used to for their separation. The first spot eluted from the column using this mobile phase was **234**, followed by **231**. Except for the cases of ILs **178d**, **181d**, **178f**, **181f**, **181b** and **181e**, **231** was the observed product in using the novel ILs as reaction solvents. Selectivity was quoted for non-hydrogenolysed product (**234**). The factors affecting hydrogenation in the novel ILs that were investigated included: IL anion, IL cation, IL purification, hydrogenolysis study and IL recyclability.

4.6.1 Effect of IL anion on hydrogenation

Using the [$OctOSO_3$] and [NTf_2] ILs (**181d** and **181f**), 100 % conversion and selectivity were achieved. With differing anions, the propoxyethoxy derivative (**181**) is successful in preventing hydrogenolysis in the case of the [BF_4] IL. Good selectivity is also observed for this cation using the [$N(CN)_2$] IL (Table 4.36).

	181			
Anion	**Time (h)**	**Temp (º C)**	**Conversion (%)**	**Selectivity (%)**
$N(CN)_2$ **e**	48	55	87	92
BF_4 **b**	48	55	100	100
$OctOSO_3$ **f**	48	60	100	100
NTf_2 **d**	48	55	100	100

Table 4.36 Anion effect with **181** cation

4.6.2 Imidazolium moiety

With the **178d** IL, no difference in selectivity or conversion is seen when a methyl group is added to the C_2 position in the IL (**189d**) (Table 4.37).

NTf_2 ILs (d)			
Solvent	**Time (h)**	**Conversion (%)**	**Selectivity (%)**
189	48	100	0
178	5	100	0
	24	100	0
	48	100	0

Table 4.37 Effect of imidazolium substitution with [NTf_2] ILs

In the case of the [$N(CN)_2$] ILs (**e**), little difference is evident between the two sets of results for differing cations(Table 4.38).

$N(CN)_2$ ILs (e)		
Solvent	**Conversion (%)**	**Selectivity (%)**
182	87	92
190	85	91

Table 4.38 Effect of imidazolium substitution with [$N(CN)_2$] ILs

4.6.3 Effect of IL purification on hydrogenation

4.6.3.1 Halide removal

The removal of excess halide from **185c** increases the selectivity from 30 % to 97 %, albeit with a compromise in percentage conversion (91 %) (Table 4.39).

185c		
Halide ($AgNO_3$ test)	**Conversion (%)**	**Selectivity (%)**
Positive	100	30
negative	91	97

Table 4.39 Effect of halide removal (**185c**)

4.6.4 Effect of selected IL on hydrogenolysis of substrate

Using ILs **181d**, **178f** and **181f**, it was found that hydrogenolysis of the benzyl ester did not occur after 48h of hydrogenation. A detailed study was launched to investigate this effect in similar ILs and to investigate various effects on this reaction. The effect of

catalyst loading, as well as the solvent effect was investigated during hydrogenations of benzyl cinnamate with various ILs (Table 4.40).

Solvent	Cat. Loading (g)	Time (h)	Conversion (%)	Selectivity (%)
178d	0.01	24	100	0
	0.005	24	100	0
181d	0.01	24	100	0
	0.005	24	100	100
	0.005	24	100	100
	0.005	48	100	100
	0.0025	24	32	100
178f	0.01	24	100	53
	0.005	24	10	100
	0.0025	24	5	100
	0.005	48	19	100
	0.0025	48	0	0
181f	0.005	24	100	100
	0.01	48	100	56
	0.005	48	11	100
	0.0025	48	0	0
[bmim][NTf_2] **107**	0.005	24	100	0
[bmim][$OctOSO_3$] **230**	0.005	24	100	0
THF	0.005	24	100	0
Ethyl acetate	0.005	24	100	0
methanol	0.005	24	100	0

Table 4.40 Hydrogenolysis of benzyl cinnamate

The least amount of catalyst effective in inducing 100 % conversion was 0.005g. Using half this value, only 32 % conversion was achieved after 24h with IL **181d**. The [$OctOSO_3$] ILs (**178f** and **181f**) gave promising results in terms of selectivity; however this was only achieved when conversion was low for IL **178f**, but with optimal conversion for IL **181f**. The most compelling results from this data set are obtained using ILs **178d** and **181f**. Using 0.005 g catalyst, after 24 h, 100 % conversion and

selectivity were obtained. More surprising is the fact that the selectivity was retained up to 48h, thus suggesting that hydrogenolysis of the compound in this IL system only occurs with the unsaturated ester. More evidence is observed when the non-hydrogenolysed reduced product (**234**) is further subjected to hydrogenation conditions using an increased amount of catalyst. No hydrogenolysis is observed (Table 4.41). The significance of this result is based on the fact that IL **181d** completely prevents hydrogenolysis of the benzyl ester.

Solvent	Cat. Loading (g)	Time (h)	Conversion (%)	Selectivity (%)
181d	0.01	24	100	0

Table 4.41 Hydrogenation of benzyl 3-phenylpropanoate

4.6.5 Effect of IL recycling on hydrogenation

The system used to obtain 100 % selectivity using IL **181d** was recycled 8 times with no loss in activity (Table 4.42).

181d		
Exp./Recycle	**Conversion (%)**	**Selectivity (%)**
E1	100	100
R1	100	100
R2	100	100
R3	100	100
R4	100	100
R5	97	100
R6	91	100
R7	91	100
R8	81	100

Table 4.42 Recycling of IL **181d** system

After the fourth recycle, the selectivity remains constant, but the conversion decreases slightly to 91 % upon recycle 7. It is only upon recycle 8 that a significant drop in conversion is observed (81 %).

Varying catalytic amounts were tested for the hydrogenation of benzyl cinnamate using IL **181f** (Table 4.43).

181f (24 h)		
Cat. Loading (g)	**Conversion (%)**	**Selectivity (%)**
0.005	100	100
0.006	100	68
0.007	100	55
0.008	100	26
0.009	100	25

Table 4.43 Varying catalytic amount for the hydrogenation of benzyl cinnamate in **181f**

As can be seen from the results displayed in Table 4.43, the increasing amount of catalyst favours hydrogenolysis with optimum conditions being observed using 0.005 g catalyst.

The effect of cation chain length and the number of oxygens in the side chain was investigated to determine whether it was only the cation from ILs **181d** and **181f** that gave the best selectivity (Table 4.44).

0.005 g catalyst, 24 h, 100 % conversion	
Solvent (d)	**Selectivity (%)**
179	7
180	0
182	34
185	44
187	0

Table 4.44 Effect of ILs of differing cation on the selective reduction of benzyl cinnamate

It is evident from the results obtained that any difference in the length of the side chain or the number of oxygens in it negatively affects the selectivity of the reaction. This reaction is therefore sensitive to changes in IL composition concerning the IL cation.

4.6.6 NMR spectra

From the crude ^{1}H NMR spectrum, the ratio of **224** to **231** to **234** can be established (Figure 4.18).

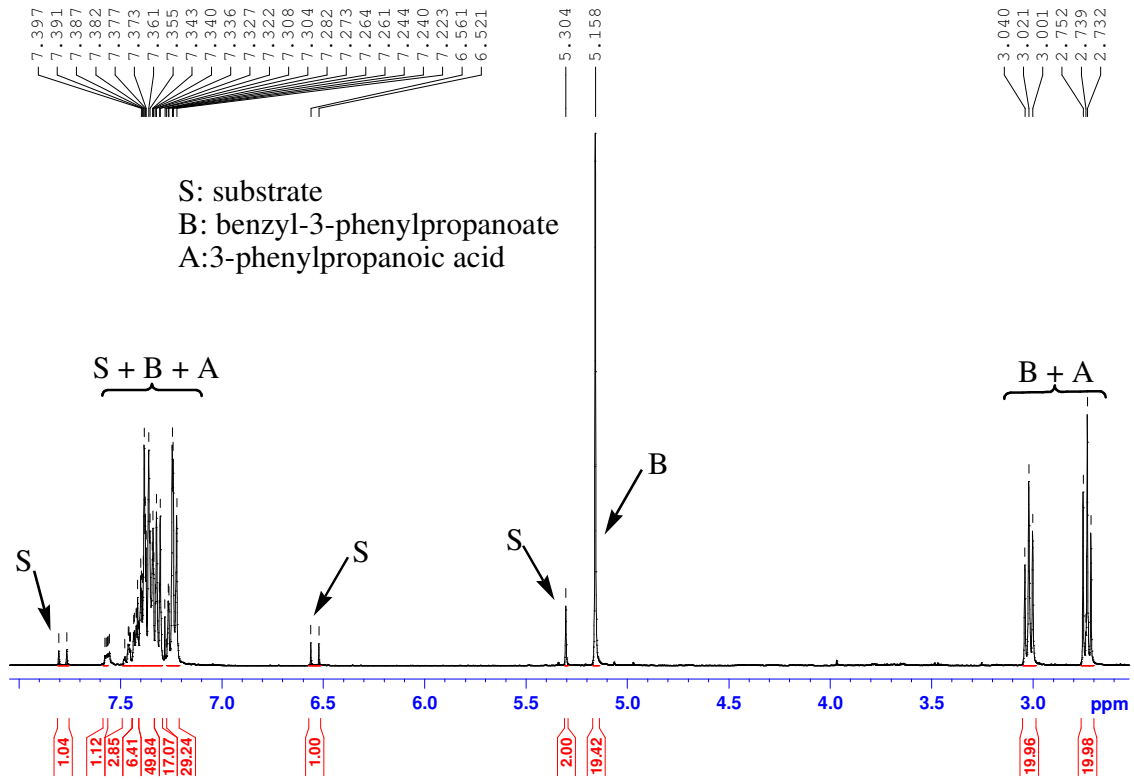


Figure 4.18 Crude ^{1}H NMR spectrum

The doublet signals for the olefinic peaks of the substrate are separate from the singlet signal for the methylene group of **234**. The two triplet signals in the aliphatic region of the spectrum comprise the signals for **234** and **231**. The amount of acid can however be easily calculated by subtraction from the amount of **234** determined by its singlet peak at ~ 5.2 ppm. The crude product mixture of **231** and **234** can be separated using column chromatography with mobile phase ethyl acetate: hexane, 80:20. **234** elutes first from the column.

4.7 Various substrates

A short study of a variety of substrates with various functional groups was tested in four selected ILs (**178d**, **181d**, **178f** and **181f**) (Table 4.45). For the case of the hydrogenation of allyl cinnamate (**227**), two products were observed, propyl 3-phenylpropanoate (**235**) and propyl cinnamate (**236**); selectivity was quoted in terms of propyl cinnamate (**235**). For vinyl cinnamate (**228**), two products were observed, ethyl 3-phenylpropoanoate (**233**) and ethyl cinnamate (**223**); selectivity was quoted in terms of the latter (**223**). Only one product was observed in the case of the hydrogenation of cinnamamide (**226**), 3-phenylpropanamide (**237**)**,** and cinnamonitrile (**225**) that of 3-phenylpropanenitrile (**238**).

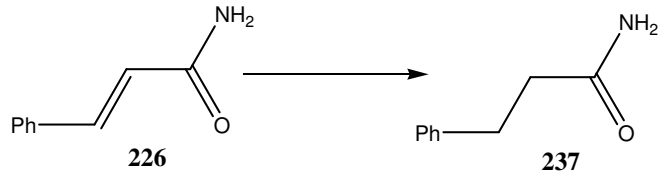
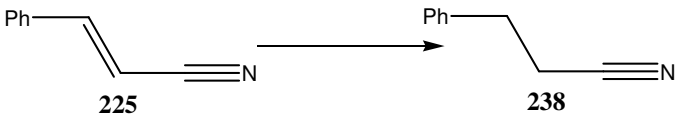
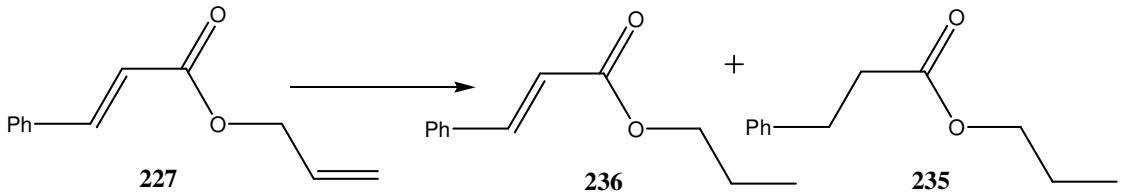
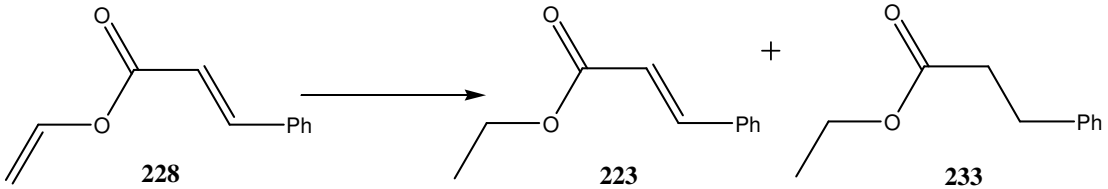
Reaction	[NTf_2] ILs		[$OctOSO_3$] ILs	
	178	**181**	**178**	**181**
 **226** **237**	100 % conversion	100 % conversion	100 % conversion	100 % conversion
 **225** **238**	100 % conversion	100 % conversion	100 % conversion	98 % conversion
 **227** **236** **235**	100 % conversion 0 % selective	100 % conversion 84 % selective	100 % conversion 0 % selective	100 % conversion 71 % selective
 **228** **223** **233**	100 % conversion 0 % selective	100 % conversion 0 % selective	100 % conversion 0 % selective	100 % conversion 49 % selective

Table 4.45 Study of various substrates

4.8 Conclusion

A range of substrates were hydrogenated in the novel ILs. The ester functionality present in the ILs did not pose a problem, except when high temperatures were required for the separation of products from the [$OctOSO_3$] ILs. In many cases, hydrolysis of this ester bond was evident, and the alcohol starting material was obtained together with the desired product. The reduction of the olefinic double bond was achieved selectively in the presence of other functional groups.

Trans-stilbene was successfully used as a test substrate for these hydrogenations in the novel ILs. The effect of the anion of the IL used was shown to affect conversion, for which the lowest result was obtained with IL **178e**. The cation side-chain however did not significantly alter results. The **178d** system was recycled 20 times, thus demonstrating the robustness of the novel ILs in these hydrogenations. In the case of *trans*-cinnamaldehyde, the ILs of [BF_4], [$N(CN)_2$] and [$OctOSO_3$] anions, displayed the poorest results, thus indicating that the anion again significantly influences the reaction. The side-chain of the IL cation was shown to have a marked influence on reaction results obtained. Only 5 % conversion was obtained with IL **186d**, although 100 % selectivity was obtained. The highest conversion obtained was using the ILs of propyl-terminating side-chains (**181d** and **185d**). **178d** gave both impressive conversion and selectivity (98 and 94 % respectively). Recycling was in some cases shown to demonstrate a positive effect on the reaction. 100 % selectivity was obtained using **185d** and **189d** upon the first recycle. Recycling of the **181d** system 16 times showed the conversion to significantly decrease, however the selectivity remained relatively constant.

Concerning *trans*-cinnamic acid and methyl and ethyl cinnamate, successful hydrogenation reactions were carried out in the novel ILs, with 100 % conversion being reached with a wide combination of IL cations and anions.

Interesting IL effects on selectivity of hydrogenation reactions were observed using the benzyl cinnamate substrate. The cation side-chain of the IL was shown to, in some cases, positively influence reaction selectivity. Regardless of IL anion (**b**, **d, e**, **f**) side-chain **e** was shown to give 100 % selectivity (ie no hydrogenolysis of the substrate). In comparison with commercially available [bmim] ILs, **181d**, **178f** and **181f** prevented hydrogenolysis of the substrate. Recycling of the **181d** system did not affect selectivity, however conversion decreased slightly over 8 recycling

experiments. Using IL **181f**, the selectivity of the reaction was shown to be sensitive to the amount of palladium catalyst used. Increasing catalyst amounts led to decreasing selectivity. 100 % selectivity was obtained using 0.005 g 10 % Pd/C catalyst, however the selectivity dramatically decreased to 25 % using 0.009 g catalyst. The selectivity obtained was also sensitive to the cation side-chain used in the reaction. Only cations **178** and **181** led to 100 % selectivity being obtained.

High percentage conversions for double bond reduction were observed using ILs **178** and **181 d** and **f**, using substrates, cinnamamide and cinnamonitrile. In the case of cinnamonitrile, the nitrile functionality was left unreduced after 48 hours of hydrogenation. The selective reduction of allyl cinnamate to propyl cinnamate was observed using ILs **181d** and **181f** (84 and 71 % selective respectively). Using vinyl cinnamate as substrate, selectivity of 49 % was only observed using IL **181f**.

4.9 Bibliography

1 H. Blaser, C. Malan, B. Pugin, F. Spindler, H. Steiner and M. Studer, *Adv. Synth. Catal.,* 2003, 345.

2 M. He and E. Min, *Catalysis Today,* 2000, **63**, 113.

3 F. D. Klingler, *Acc. Chem. Res.,* 2007, **40**, 1367.

4 S. Radl, A. Koynov, G. Tryggvason and J. Khinast, *Chemical Engineering Science,* 2008, **63**, 3279.

5 I. Vilella, S. de Miguel and O. Scelza, *J. Mol. Catal. A: Chem.: Chemical,* 2008, **284**, 161.

6 D. Schneider and M. Viljoen, *Tetrahedron,* 2002, 5307.

7 M. Cramarossa, A. Nadini, M. Bondi, P. Messi, U. Pagnoni and L. Forti, *C. R. Chimie,* 2005, **8**, 849.

8 G. Torres, S. Ledesma, E. Jablonski, S. de Miguel and O. Scelza, *Catalysis Today,* 1999, **48**, 65.

9 O. Kanie, G. Grotenbreg and C. Wong, *Angew. Chem.,* 2000, **112**, 24.

10 S. Kim, S. Jacobo, C. Chang, S. Bellone, W. Powell and J. Rokach, *Tetrahedron Lett.,* 2004, **45**, 1973.

11 K. Anderson, P. Goodrich, C. Hardacre and D. Rooney, *Green Chem.,* 2003, **5**, 448.

12 C. Boxwell, P. Dyson, D. Ellis and T. Welton, *J. Am. Chem. Soc.,* 2002, **124**, 9334.

13 R. Chan, *Pat. 4427697,* 1984.

14 X. Cheng, H. Li, W. Dai, J. Wang, y. ran and M. Qiao, *Appl. Catal. A.,* 2003, **253**, 359.

15 P. Maki-Arvela, J. Haje, T. Salmi and D. Murzin, *Appl. Catal. A.,* 2005, **292**, 1.

16 P. Gallezot and D. Richard, *Catal. Rev. Sci. Eng.,* 1998, **40**, 81.

17 P. Gallezot and D. Richard, *Catalysis Review,* 1998, **40**, 81.

18 U. K. Singh and M. A. Vannice, *Appl. Catal. A.,* 2001, **213**, 1.

19 A. Muller, J. Bowers, J. Eubanks, C. Geiger, J. Santobianco, *WO/008989*, 1999.

20 F. Bennett, A. Ganguly, V. Girijavallabhan, N. Patel, *EP0533342*, 1993.

21 P. Jadhav and H. Man, *Tetrahedron Lett.,* 1996, **37**, 1153.

22 K. Nuithitikul and M. Winterbottom, *Chem. Eng. Sci.,* 2004, **59**, 5439.

23 J. Hajek, N. Maki-Arvela, P. Salmi and T. Murzin, *J. Mol. Catal. A: Chem.,* 2004, **217**, 145.

24 J. Qui, H. Zhang, X. Wang, H. Han, C. Liang and C. Li, *React. Kinet. Catal. Lett.,* 2006, **88**, 269.

25 A. Castelijns, J. Hogeweg, S. van Nispen, *Pat. US 5811588*, 1998.

26 A. Mori, T. Mizusaki, Y. Miyakawa, E. Ohashi, T. Haga, T. Maegawa, Y. Monguchi and H. Sajiki, *Tetrahedron,* 2006, **62**, 11925.

27 J. Le Bras, D. Mukherjee, S. Gonzalez, M. Tristany, B. Ganchegui, M. Moreno-Manas, R. Pleixats, F. Henin and J. Muzart, *New J. Chem.,* 2004, **28**, 1550.

28 H. Sajiki, T. Ikawa and K. Hirota, *Tetrahedron Lett*., 2003, **44**, 8437.

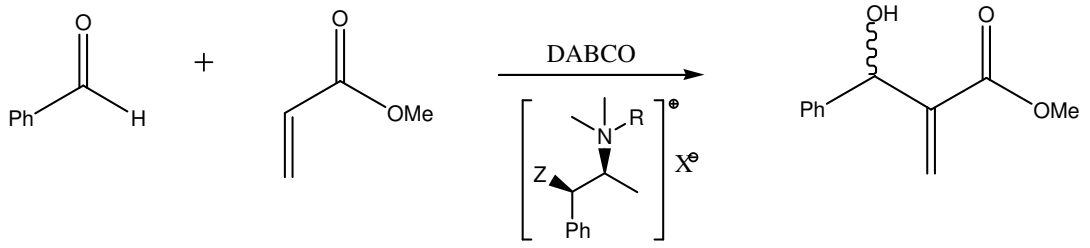
29 T. Ikawa, H. Sajiki and K. Hirota, *Tetrahedron,* 2005, **61**, 2217.

30 D. Belotti, G. Cantagrel, C. Combellas, J. Cossy, F. Kanoufi and S. Nunige, *New J. Chem.,* 2005, **29**, 761.

5 Hydrogenation in Chiral Ionic Liquids

5.1 Introduction

Chiral induction may originate from various sources including the reaction solvent.[1] The use of CILs as chiral induction solvent has been studied with promising results being obtained. Pegot *et al.*[2] achieved reasonable enantioselectivity from their CIL (chirality originating from the cation) in the Baylis-Hillman reaction. A solvent-free method using microwave irradiation was used to synthesise CILs from (-)-*N*-methylephedrine for subsequent use in the Baylis-Hillman reaction. The CILs were applied as reaction media for this asymmetric reaction between benzaldehyde and methyl acrylate (Figure 5.1).



R: C_4H_9, C_8H_{17}, $C_{10}H_{21}$, $C_{16}H_{33}$
X: OTf, PF_6
Z: OH, OAc

Figure 5.1 Baylis-Hillman reaction of benzaldehyde with methyl acrylate

Using DABCO as a Lewis base and CIL (R = C_8H_{17}, X = OTf, Z = OH) as reaction solvent, moderate yields (30 – 74 %) and moderate enantioselectivities (20 – 44 %) were obtained. Impressive enantioselectivity was obtained by Gausepohl *et al.*[3] using their CIL with chirality originating from the anion. The aza-Baylis-Hillman reaction (Figure 5.2) was used with methyl vinyl ketone and *N*-(4-bromobenzylidene)-4-toluenesulfonamide to furnish a chiral amine in modest conversions (34 – 39 %), however high enantioselectivities (71 – 84 %) were obtained.

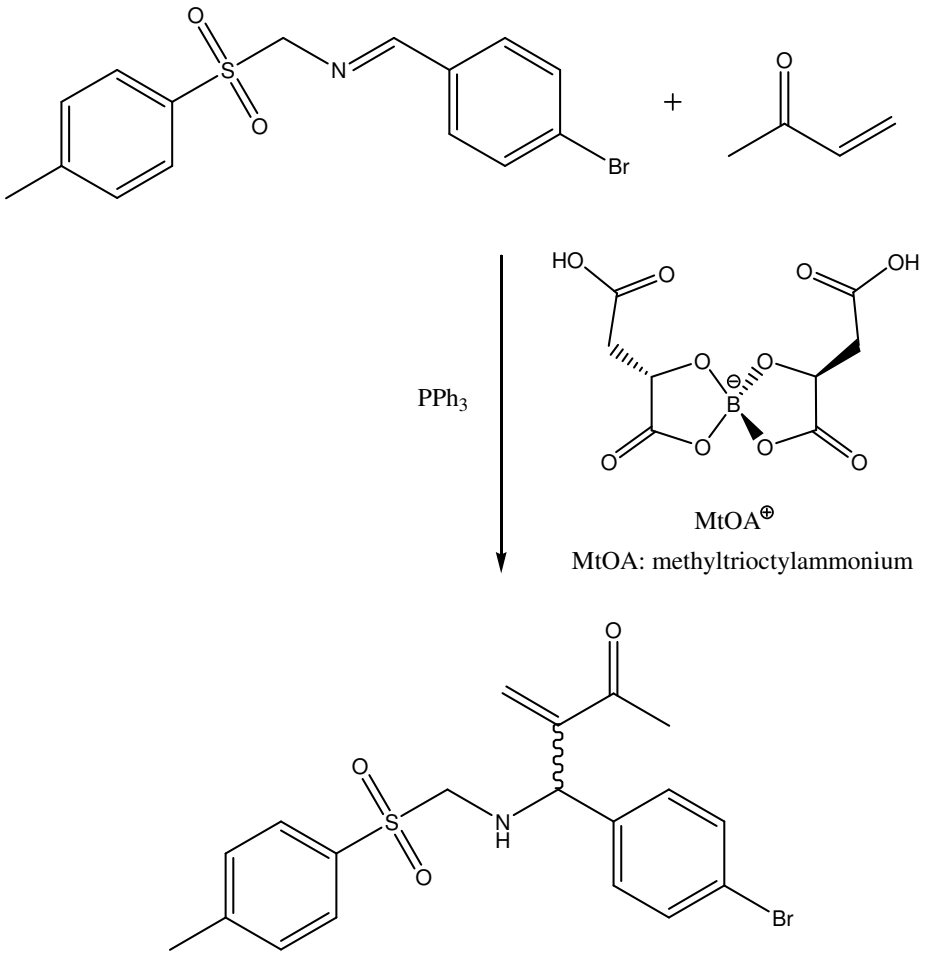


Figure 5.2 aza-Baylis-Hillman reaction

Preliminary testing of the novel CILs as reaction media was carried out using hydrogenation reactions as test systems. Using the available CILs, three substrates were briefly examined, dimethyl itaconate (**144**), tiglic acid (**239**) and α-methyl-*trans*-cinnamaldehyde (**240**) (Figure 5.3).

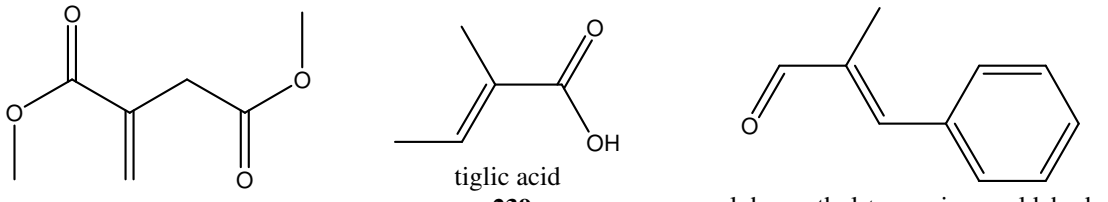


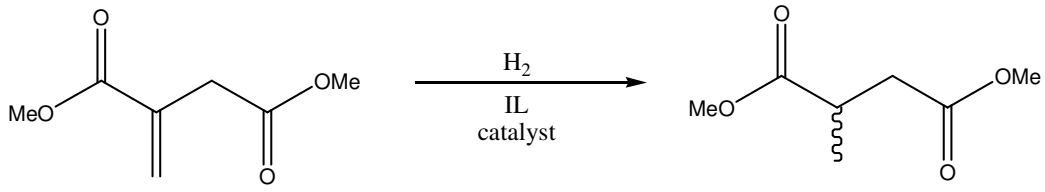
Figure 5.3 Investigated substrates

Heterogeneous catalysis using the achiral catalysts, palladium on carbon (**92**) and Adams' catalyst (**241**) was investigated. Homogeneous catalysis was also attempted using Wilkinson's catalyst (**119**) and a rhodium catalyst with a Taniaphos ligand (**242**). The potential of the CILs as enantiomeric induction media was investigated,

the sole chiral source originating from the solvent or, alternatively when the chiral rhodium catalyst was used. Each substrate is taken individually and different factors affecting hydrogenation are examined. A discussion of enantiomeric excess determination is given in section 5.5.

5.2 Dimethyl itaconate (144)

The hydrogenation of dimethyl itaconate (**144**) in the novel ILs led to one product, namely dimethyl 2-methylsuccinate (**157**) (Figure 5.4).



dimethyl itaconate
144

dimethyl 2-methylsuccinate
157

Figure 5.4 Hydrogenation of dimethyl itaconate

10 % Pd/C, Wilkinson's catalyst (**119**) and a chiral rhodium catalyst were investigated as catalysts for the hydrogenation of this prochiral substrate in achiral and chiral ILs.

5.2.1 10% Palladium on Carbon (92)

After 24 hours, 100 % conversion was obtained using ethyl acetate and **178d** respectively thus confirming the suitability of this catalyst for the reduction of dimethyl itaconate (**144**).

5.2.1.1 Lactate ILs

It is evident from the results obtained in this study that the propyl (**216e** and **f**) and pentyl (**216i** and **j**) side chains provided the best conversion, independent of their stereochemistry (Table 5.1). The ethereal oxygen present in the side chain displays a negative effect with only 50 % conversion reached after 24 hours.

Solvent	Conversion (%)
216f	100
216e	100
216h	80
216j	100
216i	100
216l	50

Table 5.1 Hydrogenation in lactate-based ILs

5.2.1.2 Mandelate ILs

The brief study of the mandelate ILs for this substrate revealed the combination of the ethereal oxygen in the side chain and the [$OctOSO_3$] side chain to have a negative effect on substrate conversion (Table 5.2).

Solvent	Conversion (%)
215c	100
217l	25

Table 5.2 Hydrogenation in mandelate-based ILs

5.2.2 Wilkinson's catalyst (119)

Wilkinson's catalyst was soluble in all CILs investigated. This catalyst was successfully immobilised in the ILs. The degree of leaching of the catalyst was examined by observation of the colour of the extract upon extraction of product from IL/catalyst mixture. A highly coloured extract indicated a greater degree of leaching, with a colourless extract being an indication of the catalyst's immobilisation in the IL.

5.2.2.1 Amount of catalyst used

The amount of catalyst deemed to be sufficient in order to induce relatively good percentage conversion was 0.05 g (1.35 mol %). Initially 0.01 g (0.27 mol %) catalyst was used, with poor results being obtained. 0.05 g catalyst was therefore used as the quantity for all subsequent reactions using Wilkinson's catalyst (Table 5.3). The extracts obtained from the ILs were slightly pale yellow indicating minimal catalyst leaching.

Solvent	Catalyst (g)	Conversion (%)
216g	0.01 g	15
215g	0.01 g	21
	0.05 g	100

Table 5.3 Effect of amount of catalyst used

5.2.2.2 Common Organic Solvents

Using 0.05 g (1.35 mol %) of Wilkinson's catalyst (**119**) in common organic solvents yielded poor percentage conversions (Table 5.4).

Solvent	Conversion (%)
DCM	7
Toluene	7
MeOH	11

Table 5.4 Hydrogenation in common organic solvents

5.2.2.3 Recycling effect

Using the racemic mandelate IL (**215c**), the recycling effect was investigated (Table 5.5).

215c	
Run	**Conversion (%)**
1	36
2	56
3	71
4	75
5	76
6	85
7	73
8	73
9	69
10	64

Table 5.5 Recycling effect (**215c**)

It was noted that an activation period for the catalyst in the IL was necessary in this case to achieve high conversion (Figure 5.5).

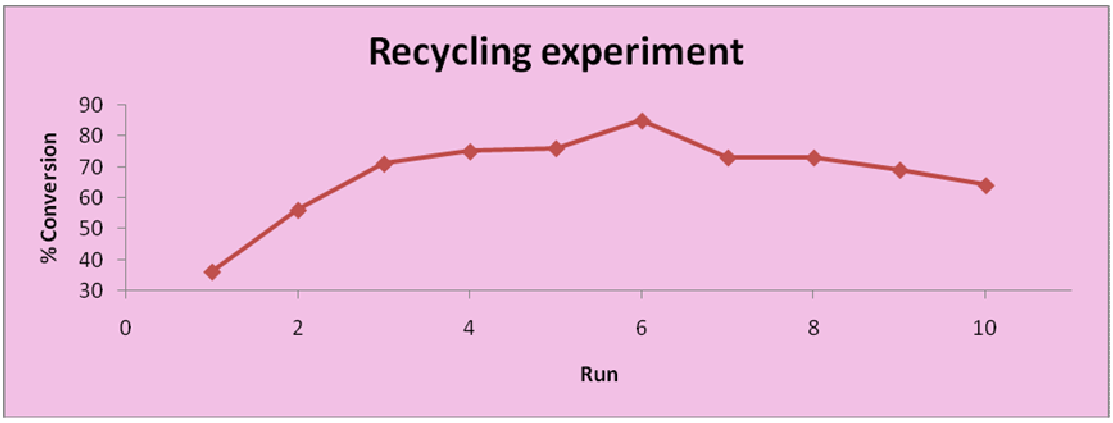


Figure 5.5 Recycling experiment

The conversion increases almost exponentially until run six, after which there is a sharp decrease by > 10 %. The conversion can then be seen to gradually decrease as far as run 10. It should be noted that upon investigation of the ^{1}H NMR after 10 runs, the IL was not degraded. This CIL had been used for 240 hours at 55 °C. Leaching of the catalyst was estimated by observation of extract colour. What was observed was that the first two reactions showed the greatest degree of leaching, with the following extracts being almost colourless.

5.2.2.4 CIL as additive

The effect of CILs as additives were investigated. **215h** as investigated as an additive with **178d** achiral IL (Table 5.6).

IL **178d**	**CIL (additive)** **215h**	
IL amount	**CIL amount**	**Conversion (%)**
2 mL	-	74
-	2 mL	100
1.8 mL	0.2 mL	74
1.5 mL	0.5 mL	100

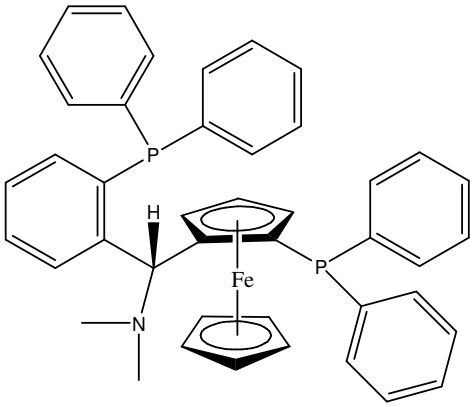
Table 5.6 CILs as additives

From the results displayed in Table 5.6 it is evident that the performance of the CIL in terms of conversion is superior to that of the IL. When 10 % CIL is added to the IL, the conversion remains the same as for the IL alone. However, 25 % CIL added is

enough to increase the conversion to 100 %. Thus, the potential of these CILs as additives has been demonstrated.

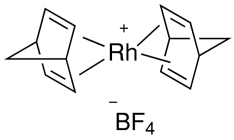
5.2.3 Rh-Taniaphos (242)

In order to test the feasibility of using the novel ILs with a chiral complex as catalyst, the Taniaphos ligand was used in conjunction with a rhodium norbornadiene complex (Figure 5.6).



(*S*)-1-diphenylphosphino-2-[(*R*)-alpha-(dimethylamino)-2-(diphenylphosphino)benzyl]ferrocene

Taniaphos



bis(norbornadiene)rhodium(I) tetrafluoroborate

Figure 5.6 Taniaphos chiral catalyst (**242**)

Two achiral ILs and a racemic mandelate IL were used as test solvents (Table 5.7).

[NTf_2] ILs	Conversion (%)
178d	100
181d	66
215c	68

Table 5.7 Hydrogenation using chiral catalyst

All ILs tested were shown to be viable solvents for the hydrogenation using this catalyst. Although IL **178d** gave the highest conversion, impressive conversion was seen also using ILs **181d** and **215c**.

5.2.4 ^{1}H NMR analysis

The peaks for dimethyl itaconate (**144**) and its reduction product (**157**) in the ^{1}H NMR spectrum were sufficiently separated that an accurate ratio of starting material to product could be obtained from a crude spectrum (Figure 5.7).

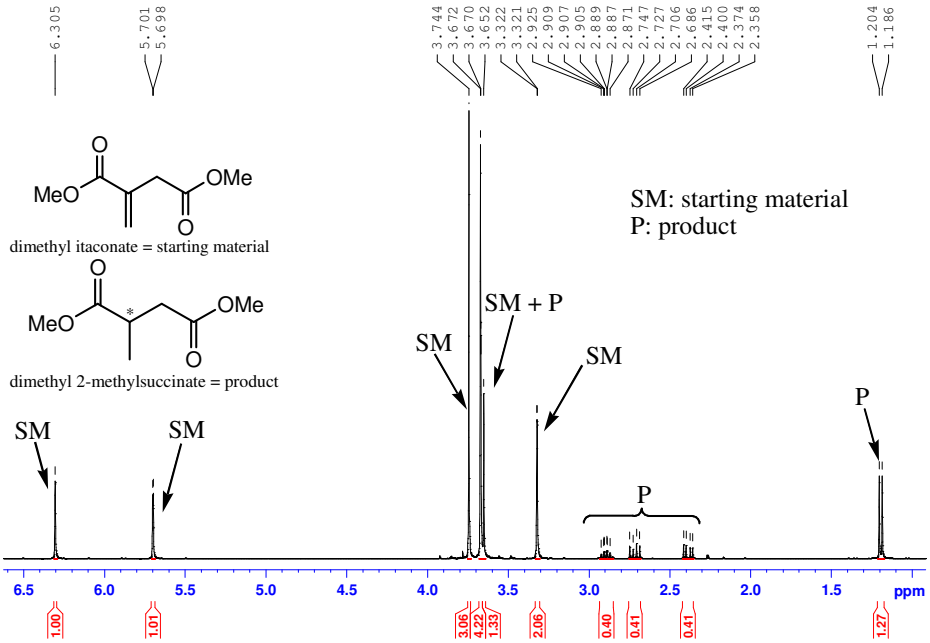


Figure 5.7 ^{1}H NMR spectrum of **144** and **157**

A determination of enantiomeric purity of a pure sample of dimethyl 2-succinate (**157**) was attempted using a europium chiral shift reagent, Eu(hfc)$_3$ (**243**). (Figure 5.8)

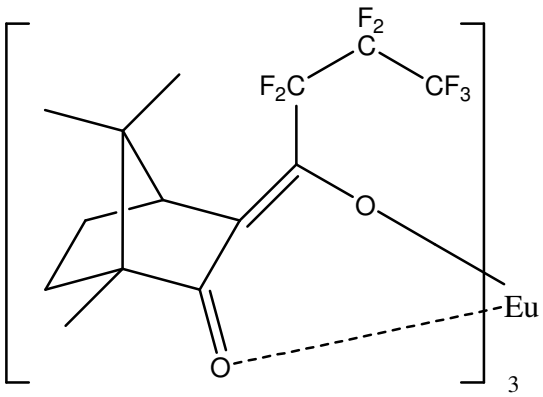


Figure 5.8 Europium chiral shift reagent (**243**)

Following addition of this chiral shift reagent to a pure sample of dimethyl 2-succinate (**157**), the signal for protons of the terminal methyl group (circled below) was split into two signals (Figure 5.9).

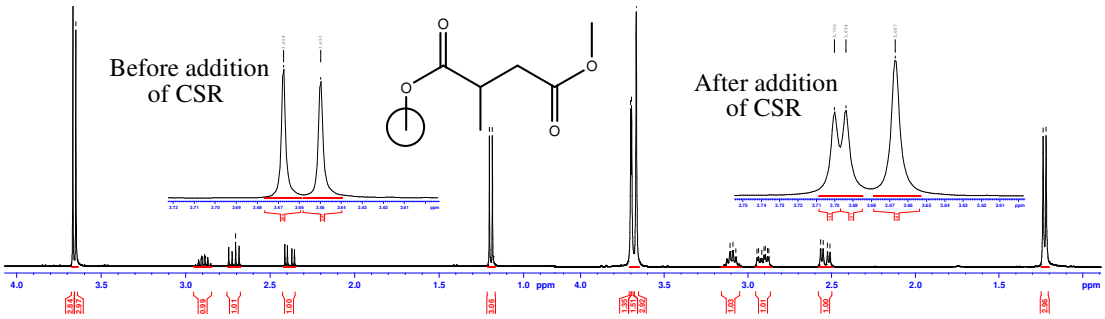
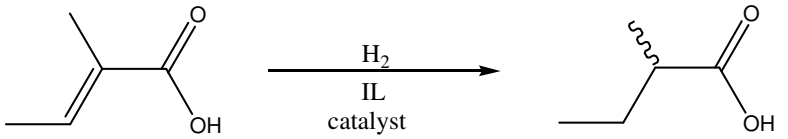


Figure 5.9 ^{1}H NMR of effect of chiral shift reagent

This method of enantiomeric determination could not be used however at this stage as the spectral resolution of the split signal was not sufficient and baseline separation was not achieved.

5.3 Tiglic acid (239)

The reduction of tiglic acid (**239**) led to the formation of 2-methylbutanoic acid (**244**) (Figure 5.10).



tiglic acid
239

2-methylbutanoic acid
244

Figure 5.10 Hydrogenation of tiglic acid

10 % Palladium on carbon (**92**), Wilkinson's catalyst (**119**) and Adam's catalyst (**241**) were used to investigate the hydrogenation of this substrate in the novel CILs.

5.3.1 10 % Pd/C (92)

All CILs displayed in Table 5.8 were tested under hydrogenation conditions using this catalyst, however no conversion was observed. Using the same amount of catalyst however, 100 % conversion was reached using ethyl acetate and achiral **178d** subsequently.

Conversion = 100 %
216d
216f
216h
216j
215c
215e
215l

Table 5.8 Hydrogenation using palladium catalyst (**92**)

Increasing the amount of catalyst used or the temperature gave however a higher conversion (Table 5.9).

216d		
Catalyst (g)	**Temperature (° C)**	**Conversion (%)**
0.05 g	55	0
0.05 g	85	81
0.15 g	55	93

Table 5.9 Increasing amount of catalyst and reaction temperature

5.3.2 Wilkinson's catalyst (119)

Using this catalyst similar conversions were obtained using common organic solvents as were obtained using the CILs (Table 5.10).

Solvent	**Conversion (%)**
Methanol	26
Ethyl acetate	8
215d	22

Table 5.10 Hydrogenation using **119**

5.3.3 Adam's catalyst (241)

Using 0.55 mol % of this catalyst, the reactions were successful, 100 % conversion was obtained for two CILs (Table 5.11).

Conversion = 100 %
215d
215a

Table 5.11 Hydrogenation using Adam's catalyst

5.3.4 NMR analysis

From the crude ^{1}H NMR of a mixture of the starting material and the product, signals for each could be clearly identified, thus facilitating facile calculation of ratios of their peaks (Figure 5.11).

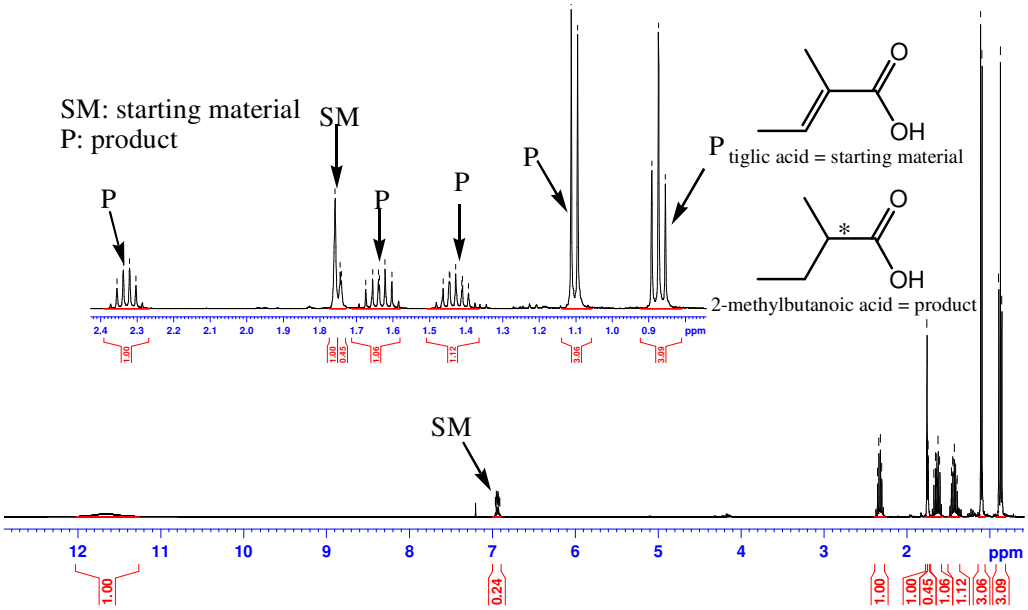


Figure 5.11 Crude ^{1}H NMR spectrum

5.4 α-methyl-*trans*-cinnamaldehyde (240)

The hydrogenation of this substrate led to a mixture of products, namely 2-methyl-3-phenylpropanal (**245**) and 2-methyl-3-phenylpropan-1-ol (**246**). (Figure 5.12).

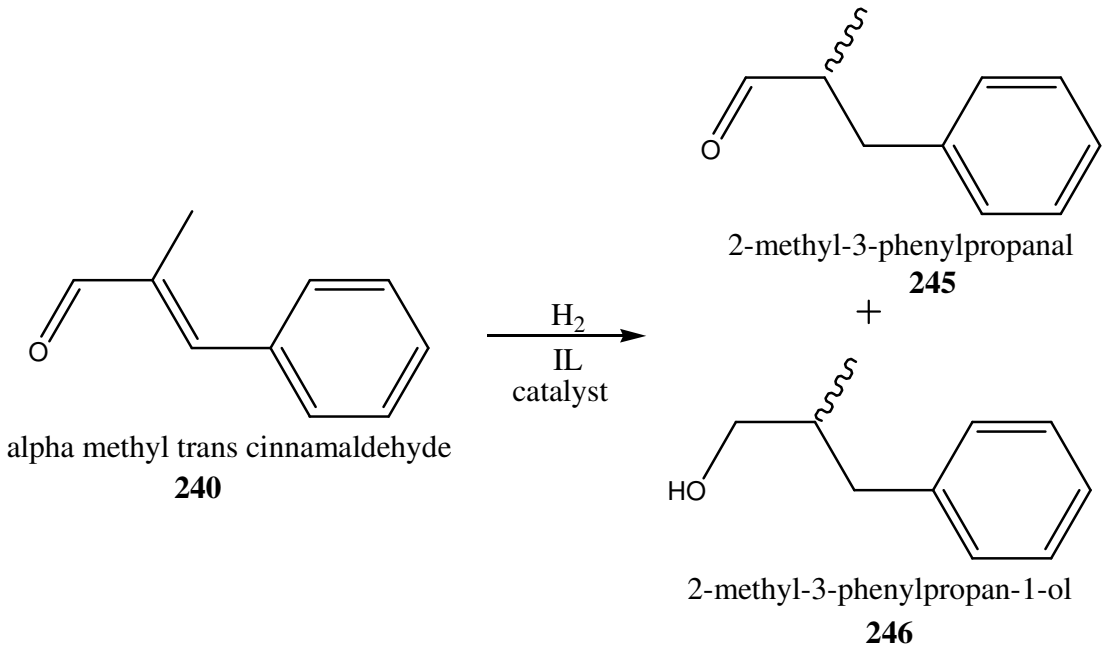


Figure 5.12 Hydrogenation of α-methyl-*trans*-cinnamaldehyde (**240**)

The hydrogenation of this substrate was initially attempted in the achiral ILs in order to establish the general ease of reduction of the sterically hindered double bond.

5.4.1 10 % Pd/C (92)

Achiral ILs were tested as reaction solvents using this catalyst. Selectivity is quoted for **245**. Hydrogenation using this catalyst was also attempted in toluene for comparison purposes (Table 5.12).

Solvent	Temperature (° C)	Selectivity (%)	Conversion (%)
Toluene	RT	67	56
178d	55	78	12
178f	80	100	11
181d	55	0	0
181f	55	0	0

Table 5.12 Hydrogenation using 10 % Pd/C catalyst (**92**)

It can be seen that the influence of an ethereal oxygen in the side chain of the IL is of more significant influence than the anion. Using both the [NTf_2] anion and [$OctOSO_3$] anion with the pentyl side chain (**178d** and **178f**), acceptable conversions are reached.

The addition of an ethereal oxygen to the side chain (**181d** and **181f**) however reduces the conversion to 0 %.

5.4.2 Adams catalyst (241)

Although the selectivity obtained using the CILs was high (100 %) a compromise in percentage conversion was observed, 34 % being the highest conversion obtained using the CILs (Table 5.13).

Solvent	Selectivity (%)	Conversion (%)
178d	55	77
216f	100	32
216k	100	22
215e	100	22
215i	100	34
215k	100	4

Table 5.13 Hydrogenation using Adams catalyst (**241**)

5.4.3 NMR analysis

Analysis of a crude ^{1}H NMR spectrum of the hydrogenation mixture of substrate and products was feasible due to the separation of the signals (Figure 5.13).

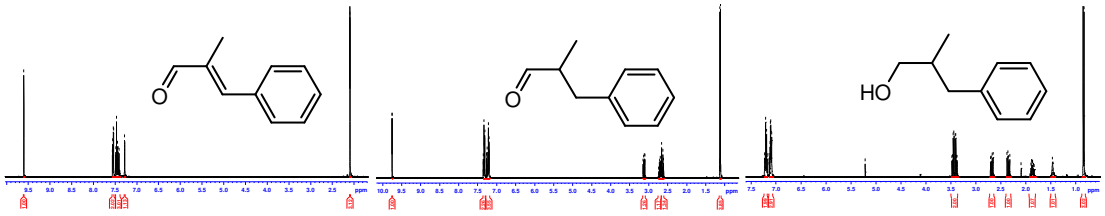


Figure 5.13 ^{1}H NMR spectra of **239**, **244** and **245**

A ^{1}H NMR spectrum of a mixture of the compounds shows that a ratio of signals could be used to determine percentage selectivity and conversion. This can be seen from an example of the crude spectrum (Figure 5.14).

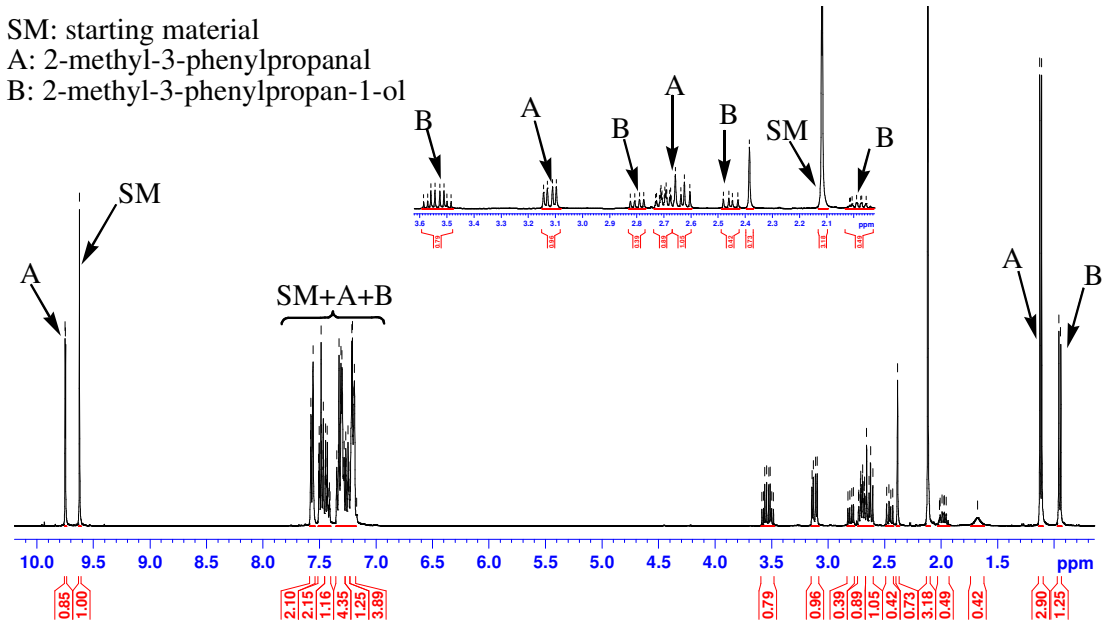


Figure 5.14 ^{1}H NMR spectrum of crude reaction mixture

5.5 Enantioselectivity

5.5.1 Dimethyl 2-methylsuccinate (157)

Chiral HPLC was used to analyse the possible enantiomeric excess of the products from the reactions. The retention time of (*R*)-dimethyl 2-methylsuccinate was shown to be approximately 5.3 minutes, followed by the (*S*)-enantiomer eluting at approximately 6.3 minutes (Figure 5.15). This was confirmed by injection of a purchased (*S*)-dimethyl 2-methylsuccinate standard from Sigma-Aldrich.

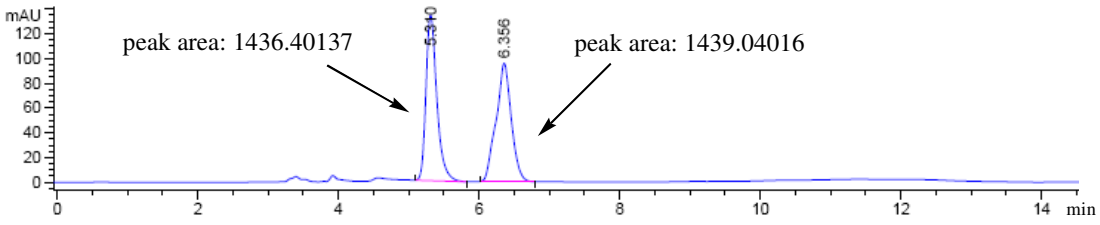


Figure 5.15 CHIRALPAK® IB column, 30 minutes isocratic, 98:2 heptane:ethanol, 1 mL/min

The optical rotation of the products was also determined. Using the (*S*)-dimethyl-2-methylsuccinate standard (c, 3.0 in acetone), $[\alpha]_D^{20} = +4°$ was obtained. All subsequent products were measured at this concentration in acetone to give 0 – 0.2 ° optical rotation. Using chiral HPLC to determine enantioselectivity however led to

misleading results. Taking as controls, products obtained in 100 % conversion from an achiral reaction (achiral solvent/catalyst), ee values ranged from 1.3 – 2.0 % ee. Thus, an error was evidently observed using this method as the % ee should have been 0 %. As the conversion decreased, an increased error in the method was observed. Again, testing products resulting from achiral reactions, an error range of 3.26 (*R*) – 15.81 (*S*) % ee was obtained. However unsuccessful the HPLC measurements, a rough value could be estimated for products of 100 % conversion as the errors were lower than those products containing residual starting material. As values lower than 3 % ee were obtained for products resulting from reactions carried out in optically pure solvents, and the optical purity obtained from optical rotation measurements was < 0.2 °, the conclusion was drawn that chiral induction from chiral solvents used did not arise. Using the chiral catalyst however, with the product resulting from 100 % conversion, 30 (*S*) % ee was obtained using chiral HPLC, this result lying far outside the errors obtained. Using the polarimeter, 3.85 ° rotation was observed, thus confirming chiral induction from the reaction of the prochiral substrate. It is thus imperative that future work in this area should continue by development of an acceptable method for enantiomeric purity of the samples obtained.

5.5.2 2-Methylbutanoic acid (244)

The products obtained from the hydrogenation of tiglic acid were derivatized to the corresponding methyl ester (**247**) for subsequent analysis of enantiomer composition using chiral GC with an MS detector.

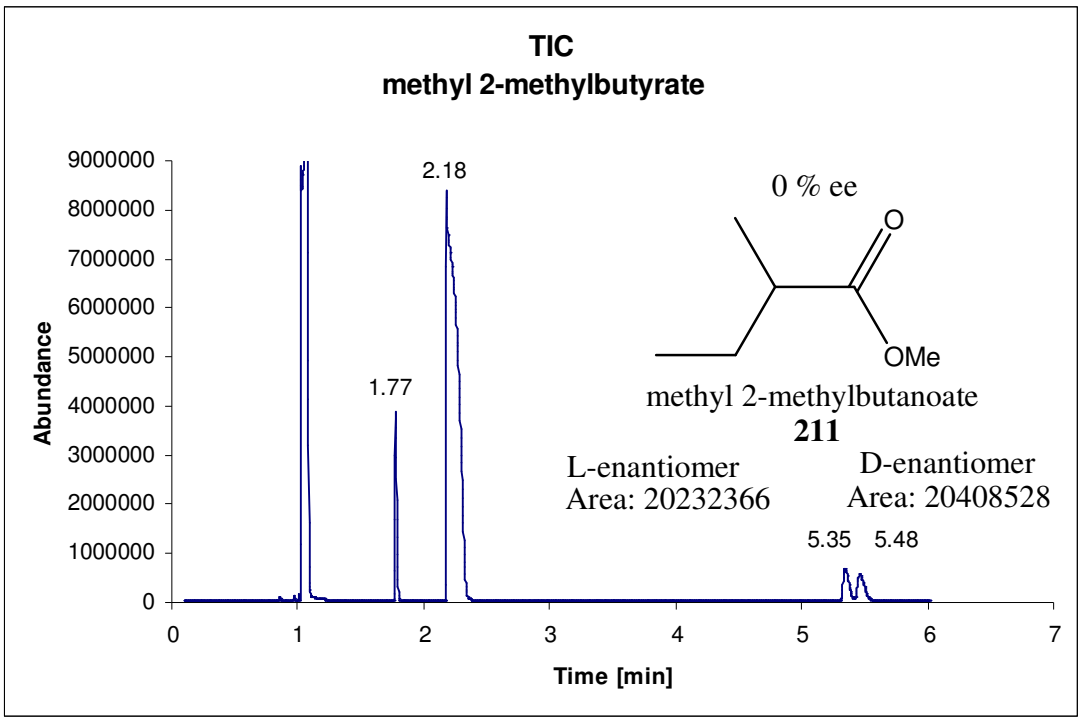


Figure 5.16 GC trace obtained using CP-Cyclodextrin-β-2,3,6-M-19 column

Due to the similar retention times of both enantiomers on the chiral GC column, optical rotation was used as an investigative method to indicate if the final product was indeed a racemic mixture. Optical rotations were carried out in acetone and all reaction products furnished racemic mixtures. The optical rotation value for a standard, *S*-(+)-2-methylbutyric acid from Aldrich (245526), was $[\alpha]_D^{20} = +19\ °$, neat. Improved GC conditions need to be developed for future enantiomeric detection of this product.

5.5.3 2-Methyl-3-phenylpropanal (245) and 2-methyl-3-phenylpropan-1-ol (246)

As of yet, we have not developed a chiral GC/HPLC method for the enantiomeric measurement of the products obtained form the hydrogenation of α-methyl-*trans*-cinnamaldehyde. Optical rotation was used thus far as a method for the determination of the optical activity of the compounds. Values obtained were < 0.2 ° with **246** carried out in acetone (c = 4.2)[4] and **245** also carried out in acetone (c = 1.25).[5]

Future work will entail the development of a method for accurate determination of % ee obtained using chiral GC or HPLC.

5.6 Conclusion

Successful hydrogenation of three prochiral substrates was achieved in the novel achiral and chiral ILs. In the case of dimethyl itaconate, novel CILs were shown to be suitable solvents for its hydrogenation. Good conversion was obtained using the lactate ILs of alkyl terminating side-chain. The presence of an oxygen atom in the side-chain however showed the poorest conversion. This effect was also noted, albeit more pronounced, with mandelate ILs. Interestingly, using 1.35 mol % Wilkinson's catalyst, superior results were obtained in the novel ILs in comparison with organic solvents. This homogeneous catalyst was also recycled numerous times in a novel IL with minimal leaching being observed. A chiral rhodium catalyst was also successfully used with 100 % conversion being obtained in a novel IL. Using tiglic acid as substrate, Adam's catalyst was shown to have superior activity to Pd/C in the hydrogenation carried out in the novel ILs. 100 % conversion was obtained using this catalyst in a number of novel ILs. In the case of α-methyl-*trans*-cinnamaldehyde, Adams catalyst was shown to be not as active for this substrate. Although low conversions were obtained in the novel ILs using this catalyst, selectivity towards **245** remained at an impressive 100 %.

Although chiral induction did not arise from these novel chiral solvents, they showed promise as alternative reaction media. The fact that the CILs were sufficiently robust to endure elevated temperatures and reaction times with no indication of degradation displayed their possible future use. The CILs demonstrated potential as chiral additives as well as immobilizing media for homogeneous catalysts. In terms of selectivity, impressive results were obtained for the substrate α-methyl-*trans*-cinnamaldehyde, even though conversion was poor.

In order for satisfactory enantioselectivity results to be obtained, analytical method development is required in the future for the determination of possible chiral induction.

5.7 Bibliography

1 C. Reichardt, S*olvents and Solvent effects in Organic Chemistry*, Wiley-VCH, Weinheim, 2003.

2 B. Pegot, G. Vo-Thanh, D. Gori, A. Loupy, *Tetrahedron Lett.,* 2004, **45**, 6425-6428.

3 R. Gausepohl, P. Buskens, J. Kleinen, A. Bruckmann, C. Lehmann, J. Klankermayer and W. Leitner, *Angew. Chem. Int. Ed.,* 2006, **45**, 3689.

4 A. Myers, B. Yang and H. Chen, *Organic Synthesis,* 2004, **77**, 29.

5 J. Cadogan and P. Rhodes, *Dictionary of Organic Compounds*, **5**.

Appendix A

Experimental Section

Experimental work

Introduction

Chemicals

All chemicals were purchased from Aldrich, with the exception of $LiNTf_2$, which was purchased from Solvionic. Methanol, ethanol, diethyl ether and triethylamine were dried over molecular sieves and distilled before use. 1-butanol, 1-pentanol, 1-octanol, 1-decanol, 2-methoxyethanol, 2-ethoxyethanol, 2-propoxyethanol, 2-butoxyethanol, 2- (2-methoxy ethoxy) ethanol, 2- (2-ethoxy ethoxy) ethanol, 2-(2-propoxyethoxy) ethanol, 2-(2-butoxyethoxy)ethanol, 2-(2-(2-methoxyethoxy)ethoxy)ethanol, and 1-decanol were dried over molecular sieves and used without further purification. 1,2-Dimethylimidazole was distilled before use. THF was dried over sodium wire, then sodium benzophenone, and distilled before use. DCM and ACN were dried over calcium hydride, and distilled before use. Acetone was dried over potassium carbonate then distilled before use.

NMR Analysis

All NMR analysis was carried out on a Bruker 400 MHz spectrometer, operating at 400 MHz for ^{1}H NMR and 100 MHz for ^{13}C NMR, in deuterated chloroform, acetone, methanol or water. Chemical shifts are measured in parts per million (ppm) and coupling constants (*J*) are measured in Hertz (Hz). Numbering of specific protons and carbons of the compounds is assigned for all alkylating agents and bromide salts. Numbering is then assigned for the first outlined compound of each anion. For the chiral materials, numbering is performed on either the racemic version or an optically pure version of the compound.

Splitting patterns are noted as follows: s: singlet; d: doublet; t: triplet; q: quartet; dd: doublet of doublets; tt: triplet of triplets; tq: triplet of quartets; br: broad

LC/MS

Liquid chromatography time-of-flight mass spectrometry was recorded on a Waters Corp. Liquid Chromatography-Time of flight mass spectrometer from Micromass MS Technologies Centre. High resolution mass spectrometry was obtained for all bromide ILs. Low resolution mass spectrometry was obtained for all ILs including bromide

salts. Mass spectrometry data for the starting materials was not obtained due to the reactivity of these compounds.

GC/MS

Gas chromatography mass spectrometry was carried out on a Hewlett Packard HP 6890 Series GC System and a Hewlett Packard 5973 Mass Selective Detector. This analysis was carried out by Dilip Rai at UCD.

IR analysis

All IR analysis was carried out on a Perkin Elmer FT-IR spectrum GX spectrometer using a KBr disc or thin film on salt plates

Optical Rotation

All optical rotation measurements were carried out on a Perkin Elmer 343 Polarimeter in chloroform or acetone at 25 ºC.

Melting point

All melting point measurements were carried out on a Griffin melting point apparatus and values are expressed in degrees celcius (º C).

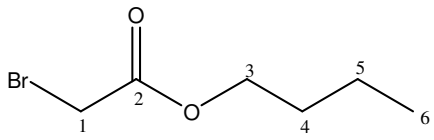
X-Ray Crystallography

This analysis was carried out by Helge Müller-Bunz at UCD.

Chapter 2 Experimental

Achiral α-bromoestes

Representative procedure for the preparation of achiral α bromoestes (butyl 2-bromoacetate) (176a)



To a stirred solution of DCM (350 mL), butanol (34.04 g, 460 mmol), and triethylamine (69.33 mL, 500 mmol) under a nitrogen atmosphere at -78 ºC was added dropwise bromoacetyl bromide (92.92 g, 460 mmol). After stirring at -78 ºC for 3 h, the reaction mixture was allowed warm up to -20 ºC and quenched by addition of water (60 mL). The organic phase was washed with distilled water (3 x 60 mL), saturated ammonium chloride (3 x 60 mL), saturated sodium bicarbonate (3 x 60 mL) and brine (2 x 60 mL). The organic phase was then dried over magnesium sulfate, filtered and solvents removed via rotary evaporation to yield the crude product. This crude product was then distilled under high vacuum to yield a pale yellow liquid in 68 % yield (60.95 g, 313 mmol).

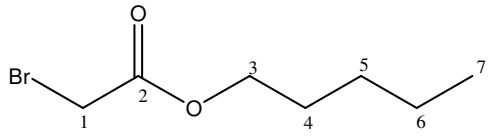
Molecular formula $C_6H_{11}BrO_2$

Molecular weight 195 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.10 (t, *J* = 6.7 Hz, 2H, *H3*), 3.75 (s, 2H, *H1*), 1.60 (tt, *J* = 6.7, 7.2 Hz, 2H, *H4*), 1.36 (tq, *J* = 7.2, 7.4 Hz, 2H, *H5*), 0.95 (t, *J* = 7.4 Hz, 3H, *H6*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.38 (*C*O), 66.19 (O*C*H_2), 30.42 (*C*H_2), 26.00 (*C*H_2), 19.00 (*C*H_2), 13.67 (*C*H_3)

Pentyl 2-bromoacetate (176b)



Slightly pale yellow liquid

The title compound was prepared from pentan-1-ol (44.00 g, 500 mmol) and bromoacetyl bromide (101.00 g, 500 mmol) according to the general procedure in 64 % yield (66.88 g, 320 mmol).

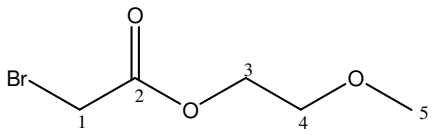
Molecular formula $C_7H_{13}BrO_2$

Molecular weight 209 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.09 (t, *J* = 6.8 Hz, 2H, *H3*), 3.75 (s, 2H, *H1*), 1.61-1.54 (m, 2H, *H4*), 1.28-1.23 (m, 4H, *H's 5 and 6*), 0.84 (t, *J* = 7.0 Hz, 3H, *H7*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.35 (*C*O), 66.45 (O*C*H_2), 28.09 (*C*H_2), 27.87 (*C*H_2), 26.01 (*C*H_2), 22.27 (*C*H_2), 13.94 (*C*H_3)

2-Methoxyethyl 2-bromoacetate (176c)



Pale yellow liquid

The title compound was prepared from methoxyethanol (34.96 g, 460 mmol) and bromoacetyl bromide (92.92 g, 460 mmol) according to the general procedure in 70 % yield (63.43 g, 322 mmol).

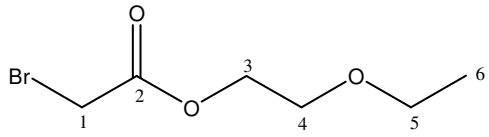
Molecular formula $C_5H_9BrO_3$

Molecular weight 197 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.27 (t, *J* = 4.6 Hz, 2H, *H3*), 3.82 (s, 2H, *H1*), 3.56 (t, *J* = 4.6 Hz, 2H, *H4*), 3.33 (s, 3H, *H5*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.23 (*C*O), 69.99 (O*C*H_2), 65.17 (*C*H_2O), 58.97 (*C*H_3), 25.86 (*C*H_2)

2-Ethoxyethyl 2-bromoacetate (176d)



Pale yellow oily liquid

The title compound was prepared from ethoxyethanol (45.00 g, 500 mmol) and bromoacetyl bromide (101.00, 500 mmol) according to the general procedure in 60 % yield (63.30 g, 300 mmol).

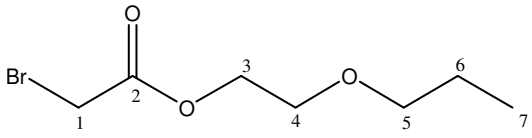
Molecular formula $C_6H_{11}BrO_3$

Molecular weight 211 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.27 (t, *J* = 4.7 Hz, 2H, *H3*), 3.83 (s, 2H, *H1*), 3.61 (t, *J* = 4.7 Hz, 2H, *H4*), 3.50 (q, *J* = 7.1 Hz, 2H, *H5*), 1.17 (t, *J* = 7.1 Hz, 3H, *H6*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.34 (*C*O), 67.95 (O*C*H_2), 66.75 (*C*H_2O), 65.47 (O*C*H_2), 25.91 (*C*H_2), 15.10 (*C*H_3)

2-Propoxyethyl 2-bromoacetate (176e)



Pale brown oily liquid

The title compound was prepared from propoxyethanol (47.84 g, 460 mmol) and bromoacetyl bromide (92.92 g, 460 mmol) according to the general procedure in 83 % yield (85.91 g, 382 mmol).

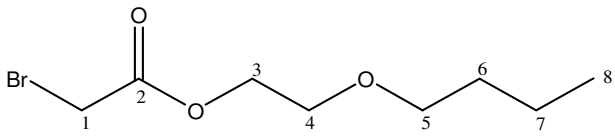
Molecular formula $C_7H_{13}BrO_3$

Molecular weight 225 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.34 (t, *J* = 4.6 Hz, 2H, *H3*), 3.88 (s, 2H, *H1*), 3.67 (t, *J* = 4.6 Hz, 2H, *H4*), 3.47 (t, *J* = 6.9 Hz, 2H, *H5*), 1.66 (tq, *J* = 6.9, 7.3 Hz, 2H, *H6*), 0.94 (t, *J* = 7.3 Hz, 3H, *H7*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.31 (*C*O), 73.07 (O*C*H_2), 68.10 (*C*H_2O), 65.42 (O*C*H_2), 25.90 (*C*H_2), 22.81 (*C*H_2), 10.52 (*C*H_3)

2-Butoxyethyl 2-bromoacetate (176f)



Pale yellow liquid

The title compound was prepared from butoxyethanol (54.28 g, 460 mmol) and bromoacetyl bromide (92.92 g, 460 mmol) according to the general procedure in 75 % yield (82.46 g, 345 mmol).

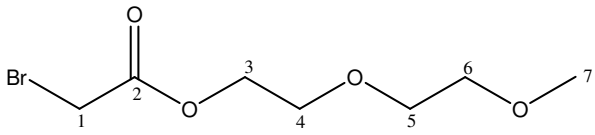
Molecular formula $C_8H_{15}BrO_3$

Molecular weight 239 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.32 (t, *J* = 4.6 Hz, 2H, *H3*), 3.88 (s, 2H, *H1*), 3.65 (t, *J* = 4.6 Hz, 2H, *H4*), 3.47 (t, *J* = 6.8 Hz, 2H, *H5*), 1.61 (tt, *J* = 6.8, 7.1 Hz, 2H, *H6*), 1.43 (tq, *J* = 7.1, 7.4 Hz, 2H, *H7*), 0.92 (t, *J* = 7.4 Hz, 3H, *H8*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.27 (*C*O), 71.19 (O*C*H_2), 68.12 (*C*H_2O), 65.39 (O*C*H_2), 31.57 (*C*H_2), 25.87 (*C*H_2), 19.20 (*C*H_2), 13.88 (*C*H_3)

2-(2-Methoxyethoxy)ethyl 2-bromoacetate (176g)



Colourless liquid

The title compound was prepared from methoxyethoxyethanol (54.00 g, 450 mmol) and bromoacetyl bromide (90.90 g, 450 mmol) according to the general procedure in 62 % yield (67.24 g, 279 mmol).

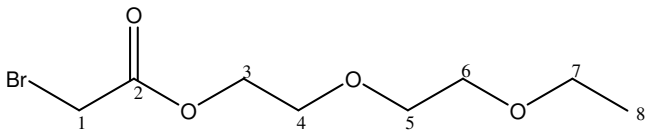
Molecular formula $C_7H_{13}BrO_4$

Molecular weight 241 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.31 (t, *J* = 4.6 Hz, 2H, *H3*), 3.86 (s, 2H, *H1*), 3.71 (t, *J* = 4.6 Hz, 2H, *H4*), 3.63-3.62 (m, 2H, *H5*), 3.53-3.51 (m, 2H, *H6*), 3.34 (s, 3H, *H7*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.24 (*C*O), 71.81 (O*C*H_2), 70.52 (*C*H_2O), 68.75 (O*C*H_2), 65.27 (*C*H_2O), 59.07 (O*C*H_3), 25.91 (*C*H_2)

2-(2-Ethoxyethoxy)ethyl 2-bromoacetate (176h)



Pale yellow liquid

The title compound was prepared from ethoxyethoxyethanol (20.10 g, 150 mmol) and bromoacetyl bromide (40.40 g, 200 mmol) according to the general procedure in 61 % yield (23.33 g, 91.4 mmol).

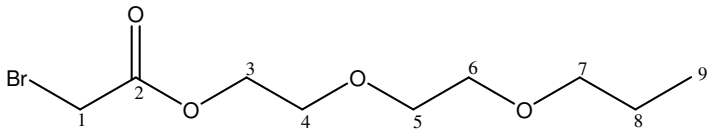
Molecular formula $C_8H_{15}BrO_4$

Molecular weight 255 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.34 (t, *J* = 4.6 Hz, 2H, *H3*), 3.88 (s, 2H, *H1*), 3.74 (t, *J* = 4.6 Hz, 2H, *H4*), 3.66 (t, *J* = 4.0 Hz, 2H, *H5*), 3.60 (t, *J* = 4.0 Hz, 2H, *H6*), 3.53 (q, *J* = 6.9 Hz, 2H, *H7*), 1.22 (t, *J* = 6.9 Hz, 3H, *H8*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.27 (*C*O), 71.20 (O*C*H_2), 70.45 (*C*H_2O), 69.90 (O*C*H_2), 66.72 (*C*H_2O), 65.32 (O*C*H_2), 25.90 (*C*H_2), 15.15 (*C*H_3)

2-(2-Propoxyethoxy)ethyl 2-bromoacetate (176i)



Pale yellow oily liquid

The title compound was prepared from propoxy ethoxyethanol (68.08 g, 460 mmol) and bromoacetyl bromide (92.92 g, 460 mmol) according to the general procedure in 73 % yield (90.33 g, 336 mmol).

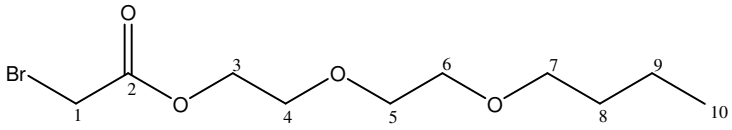
Molecular formula $C_9H_{17}BrO_4$

Molecular weight 269 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.36 (t, *J* = 4.2 Hz, 2H, *H3*), 3.89 (s, 2H, *H1*), 3.77 (t, *J* = 4.2 Hz, 2H, *H4*), 3.70 (t, *J* = 4.4 Hz, 2H, *H5*), 3.63 (t, *J* = 4.4 Hz, 2H, *H6*), 3.59 (t, *J* = 7.1 Hz, 2H, *H7*), 3.56 (tq, *J* = 7.1, 7.3 Hz, 2H, *H8*), 1.26 (t, *J* = 7.3 Hz, 3H, *H9*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.27 (*C*O), 73.13 (O*C*H_2), 70.67 (*C*H_2O), 70.56 (O*C*H_2), 68.76 (*C*H_2O), 65.36 (O*C*H_2), 25.88 (*C*H_2), 22.74 (*C*H_2), 10.51 (*C*H_3)

2-(2-Butoxyethoxy)ethyl 2-bromoacetate (176j)



Pale yellow liquid

The title compound was prepared from butoxy ethoxyethanol (72.9 g, 450 mmol) and bromoacetyl bromide (90.9 g, 450 mmol) according to the general procedure in 72 % yield (91.69 g, 324 mmol).

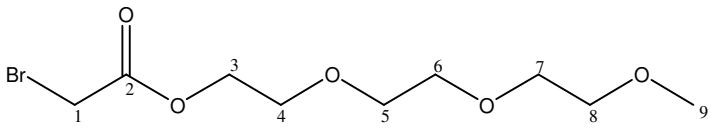
Molecular formula $C_{10}H_{19}BrO_4$

Molecular weight 283 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.30 (t, *J* = 4.6 Hz, 2H, *H3*), 3.85 (s, 2H, *H1*), 3.71 (t, *J* = 4.6 Hz, 2H, *H4*), 3.62-3.58 (m, 2H, *H5*), 3.56-3.51 (m, 2H, *H6*), 3.43 (t, *J* = 6.8 Hz, 2H, *H7*), 1.54 (tt, *J* = 6.8, 7.2 Hz 2H, *H8*), 1.34 (tq, *J* = 7.2, 7.5 Hz, 2H, *H9*), 0.89 (t, *J* = 7.5 Hz, 3H, *H10*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.28 (*C*O), 71.32 (O*C*H_2), 71.21 (*C*H_2O), 70.68 (O*C*H_2), 68.76 (*C*H_2O), 65.37 (O*C*H_2), 31.68 (*C*H_2), 25.89 (*C*H_2), 19.24 (*C*H_2), 13.95 (*C*H_3)

2-(2-(2-Methoxyethoxy)ethoxy)ethyl 2-bromoacetate (176k)



Pale yellow liquid

The title compound was prepared from methoxy ethoxyethoxyethanol (29.52 g, 180 mmol) and bromoacetyl bromide (10.4 g, 200 mmol) according to the general procedure in 58 % yield (29.75 g, 104 mmol).

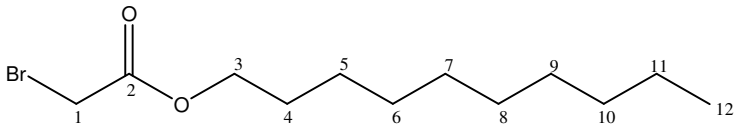
Molecular formula $C_9H_{17}BrO_5$

Molecular weight 285 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.28 (t, *J* = 4.6 Hz, 2H, *H3*), 3.81 (s, 2H, *H1*), 3.68 (t, *J* = 4.6 Hz, 2H, *H4*), 3.62-3.57 (m, 6H, *H's 5,6 and 7*), 3.50-3.43 (m, 2H, *H8*), 3.32 (s, 3H, *H9*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.25 (*C*O), 71.91 (O*C*H_2), 70.64 (*C*H_2O), 70.57 (O*C*H_2), 70.52 (*C*H_2O), 68.74 (O*C*H_2), 65.31 (*C*H_2O), 59.04 (*C*H_3), 25.84 (*C*H_2)

Decyl 2-bromoacetate (176l)



Colourless liquid

The title compound was prepared from decan-1-ol (71.10 g, 450 mmol) and bromoacetyl bromide (90.90 g, 450 mmol) according to the general procedure in 62 % yield (77.84 g, 279 mmol).

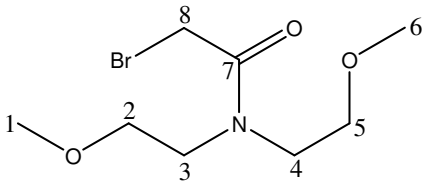
Molecular formula $C_{12}H_{23}BrO_2$

Molecular weight 279 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.18 (t, *J* = 6.8 Hz, 2H, *H3*), 3.85 (s, 2H, *H1*), 1.90 – 1.28 (m, 16H, *H's 4-11*), 0.89 (t, *J* = 6.8 Hz, 3H, *H12*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.37 (*C*O), 66.49 (O*C*H_2), 63.05 (*C*H_2), 34.09 (*C*H_2), 32.85 (*C*H_2), 32.77 (*C*H_2), 29.52 (*C*H_2), 29.49 (*C*H_2), 29.35 (*C*H_2), 29.19 (*C*H_2), 22.69 (*C*H_2), 14.13 (*C*H_3)

2-Bromo-*N*,*N*-bis(2-methoxyethyl)acetamide (199)



Pale yellow crystals

The title compound was prepared from bis(2-methoxyethyl)amine (39.90 g, 300 mmol) and bromoacetyl bromide (80.80 g, 400 mmol) according to the general procedure in 49 % yield (37.33 g, 147 mmol). Note: Purification can also be achieved by recrystallisation from diethyl ether.

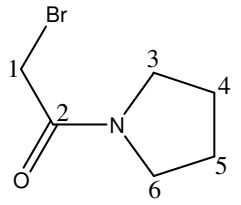
Molecular formula $C_{18}H_{26}BrNO_3$

Molecular weight 254 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.02 (s, 2H, *H8*), 3.66 (t, *J* = 5.1 Hz, 2H, *H4*), 3.55 (br s, 4H, *H's 2 and 3*), 3.53 (t, *J* = 5.1 Hz, 2H, *H5*), 3.33 (s, 6H, *H's 1 and 6*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.79 (*C*O), 70.74 (O*C*H_2), 70.27 (*C*H_2O), 59.13 (*C*H_2N), 58.94 (N*C*H_2), 50.12 (*C*H_3O), 46.90 (O*C*H_3), 27.20 (*C*H_2)

2-Bromo-1-(pyrrolin-1-yl)ethanone (200)



Pale yellow crystals

The title compound was prepared from pyrrolidine (33.50 g, 500 mmol) and bromoacetyl bromide (121.20 g, 600 mmol) according to the general procedure in 52 % yield (49.92 g, 260 mmol).

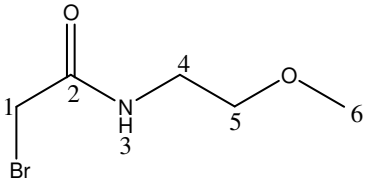
Molecular formula $C_6H_{10}BrNO$

Molecular weight 192 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 3.82 (s, 2H, *H1*), 3.55 (tt, *J* = 6.8, 6.8 Hz, 4H, *H's 3 and 6*), 2.00 (tt, *J* = 6.8, 6.8 Hz, 2H, *H4*), 1.92 (tt, *J* = 6.8, 6.8 Hz, 2H, *H5*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 165.26 (*C*O), 47.15 (N*C*H_2), 46.54 (N*C*H_2), 27.30 (*C*H_2), 26.13 (*C*H_2), 24.32 (*C*H_2)

2-Bromo-*N*-(2-methoxyethyl)acetamido (201)



Pale yellow crystals

The title compound was prepared from 2-methoxyethylamine (37.50 g, 500 mmol) and bromoacetyl bromide (111.10 g, 550 mmol) according to the general procedure in 17 % yield (16.66 g, 85.0 mmol).

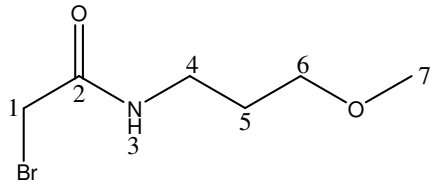
Molecular formula $C_5H_{10}BrNO_2$

Molecular weight 196 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 6.80 (br s, 1H, *H3*), 3.90 (s, 2H, *H1*), 3.49 (s, 2H, *H4*), 3.48 (s, 2H, *H5*), 3.39 (s, 3H, *H6*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 165.60 (*C*O), 70.68 (*C*H_2O), 58.89 (O*C*H_3), 39.93 (N*C*H_2), 29.12 (*C*H_2)

2-Bromo-*N*-(3-methoxypropyl)acetamido (202)



Pale yellow crystals

The title compound was prepared from 3-methoxypropan-1-amine (44.50 g, 500 mmol) and bromoacetyl bromide (111.10 g, 550 mmol) according to the general procedure in 51 % yield (53.55 g, 255 mmol).

Molecular formula $C_6H_{12}BrNO_2$

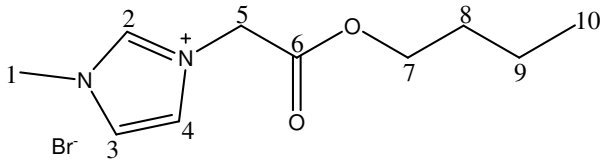
Molecular weight 210 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.22 (br s, 1H, *H3*), 3.81 (s, 2H, *H1*), 3.45 (t, *J* = 5.6 Hz, 2H, *H6*), 3.37 (q, *J* = 6.2 Hz, 2H, *H4*), 3.30 (s, 3H, *H7*), 1.78 (tt, *J* = 5.6, 6.2 Hz, 2H, *H5*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 165.39 (*C*O), 71.87 (*C*H_2O), 58.86 (O*C*H_3), 39.21 (N*C*H_2), 29.33 (*C*H_2), 28.47 (*C*H_2)

Achiral bromide salts

Representative method for the preparation of bromide salts (3-methyl-1-(butoxycarbonylmethyl)imidazolium bromide) (177a)



To a stirred solution of 1-methylimidazole (45.0 mmol, 3.69 g, 3.60 mL) in diethyl ether (60 mL) at -15 ºC under a nitrogen atmosphere was added dropwise butyl 2-bromoacetate (60.0 mmol, 11.70 g). The reaction mixture was stirred vigorously at -15 ºC for 1 h, then at RT for 24 h. The diethyl ether top phase was decanted and the IL washed with diethyl ether (2 x 20 mL), then residual solvent removed on the rotary evaporator. The product was dried under high vacuum for 8 h yielding a light orange viscous liquid in 82 % yield (10.17 g, 36.7 mmol).

Molecular formula $C_{10}H_{17}BrN_2O_2$

Molecular weight 277 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.20 (s, 1H, *H2*), 7.50 (t, *J* = 1.8 Hz, 1H, *H4*), 7.37 (t, *J* = 1.8 Hz, 1H, *H3*), 5.42 (s, 2H, *H5*), 4.15 (t, *J* = 6.7 Hz, 2H, *H7*), 4.05 (s, 3H, *H1*), 1.60 (tt, *J* = 6.7, 7.2 Hz 2H, *H8*), 1.31 (tq, *J* = 7.2, 7.4 Hz, 2H, *H9*), 0.87 (t, *J* = 7.4 Hz, 3H, *H10*)

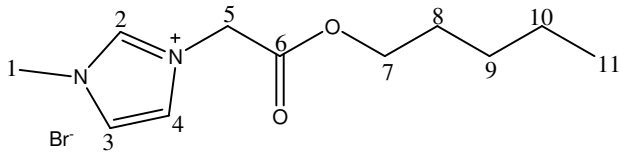
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.15 (*C*O), 138.65 (N*C*H$_2$N), 123.70 (N*C*H$_2$), 122.82 (N*C*H$_2$), 66.85 (O*C*H$_2$), 50.30 (N*C*H$_2$), 36.92 (N*C*H$_3$), 30.33 (*C*H$_2$), 18.98 (*C*H$_2$), 13.66 (*C*H$_3$)

IR (thin film on salt plate) (cm^{-1}) 3099, 2961, 2930, 2861, 1751, 1569, 1558, 1495, 1452, 1398, 1217, 1177

MS m/z, Found 197.1278 [M-Br$^-$]$^+$, Calcd. $C_{10}H_{17}N_2O_2$ 197.1290

MS *m/z*, 197.1 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

3-Methyl-1-(pentoxycarbonylmethyl)imidazolium bromide (178a)



Pale yellow viscous liquid

The title compound was prepared from 1-methylimidazole (3.69g, 45.0 mmol) and pentyl 2-bromoacetate (54.0 mmol, 11.29 g) according to the general procedure in 97 % yield (12.76 g, 43.8 mmol).

Molecular formula $C_{11}H_{19}BrN_2O_2$

Molecular weight 291 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.79 (s, 1H, *H2*), 7.30 (t, *J* = 1.8 Hz, 1H, *H4*), 7.23 (t, *J* = 1.8 Hz, 1H, *H3*), 4.95 (s, 2H, *H5*), 4.16 (t, *J* = 6.8 Hz, 2H, *H7*), 3.90 (s, 3H, *H1*), 1.65 (tt, *J* = 6.8, 7.2 Hz, 2H, *H8*), 1.30-1.23 (m, 4H, *H's 9 and 10*), 0.86 (t, *J* = 7.0 Hz, 3H, *H11*)

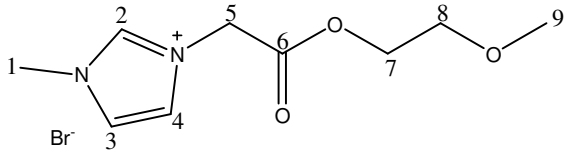
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.16 (*C*O), 138.39 (N*C*H$_2$N), 123.79 (N*C*H$_2$), 123.08 (N*C*H$_2$), 67.07 (O*C*H$_2$), 50.30 (N*C*H$_2$), 36.92 (N*C*H$_3$), 28.00 (CH$_2$), 27.79 (*C*H$_2$), 22.21 (*C*H$_2$), 13.19 (*C*H$_3$)

IR (KBr disc) (cm^{-1}) 3095, 2959, 2931, 1750, 1578, 1569, 1559, 1495, 1455, 1398, 1230, 1177

MS *m/z*, Found 211.1440 [M-Br$^-$]$^+$, Calcd. $C_{11}H_{19}N_2O_2$ 211.1447

MS *m/z*, 211.1 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

3-Methyl-1-(methoxyethoxycarbonylmethyl)imidazolium bromide (179a)



Pale brown solid

The title compound was prepared from 1-methylimidazole (120 mmol, 9.84 g) and 2-methoxyethyl 2-bromoacetate (150 mmol, 29.55 g) according to the general procedure in 89 % yield (29.92 g, 107 mmol).

Molecular formula $C_9H_{15}BrN_2O_3$

Molecular weight 279 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.33 (s, 1H, *H2*), 7.57 (t, *J* = 1.8 Hz, 1H, *H4*), 7.41 (t, *J* = 1.8 Hz, 1H, *H3*), 5.56 (s, 2H, *H5*), 4.39 (t, *J* = 4.6 Hz, 2H, *H7*), 4.10 (s, 3H, *H1*), 3.66 (t, *J* = 4.6 Hz, 2H, *H8*), 3.40 (s, 3H, *H9*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.18 (*C*O), 138.77 (N*C*H_2N), 123.73 (N*C*H_2), 122.74 (N*C*H_2), 69.84 (O*C*H_2), 65.63 (N*C*H_2), 59.03 (N*C*H_3), 50.27 (O*C*H_2), 36.94 (O*C*H_3)

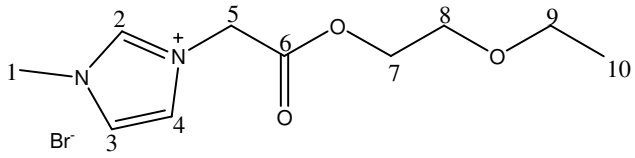
MP (°C) 53 – 55

IR (KBr disc) (cm^{-1}) 3438, 3111, 3152, 1751, 1223, 1199, 1177, 1124, 1090, 1026

MS *m/z*, Found 199.1074 $[M\text{-}Br^-]^+$, Calcd. $C_9H_{15}N_2O_3$ 199.1083

MS *m/z*, 199.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

3-Methyl-1-(ethoxyethoxycarbonylmethyl)imidazolium bromide (180a)



Pale brown solid

The title compound was prepared from 1-methylimidazole (25.0 mmol, 2.05 g) and 2-ethoxyethyl 2-bromoacetate (30.0 mmol, 6.33 g) according to the general procedure in 93 % yield (6.81 g, 23.2 mmol).

Molecular formula $C_{10}H_{17}BrN_2O_3$

Molecular weight 293 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.25 (s, 1H, *H2*), 7.61 (t, *J* = 1.8 Hz, 1H, *H4*), 7.47 (t, *J* = 1.8 Hz, 1H, *H3*), 5.54 (s, 2H, *H5*), 4.37 (t, *J* = 4.8 Hz, 2H, *H7*), 4.10 (s, 3H, *H1*), 3.68 (t, *J* = 4.8 Hz, 2H, *H8*), 3.56 (q, *J* = 7.1 Hz, 2H, *H9*), 1.22 (t, *J* = 7.1 Hz, 3H, *H10*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.31 (*C*O), 138.35 (N*C*H_2N), 123.82 (N*C*H_2), 123.04 (N*C*H_2), 67.74 (O*C*H_2), 66.70 (N*C*H_2), 65.78 (N*C*H_3), 50.31 (O*C*H_2), 36.96 (O*C*H_2), 15.11 (*C*H_3)

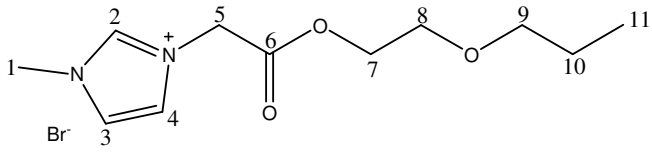
MP (°C) 24 – 26

IR (KBr disc) (cm^{-1}) 3437, 3157, 3101, 1751, 1567, 1493, 1452, 1389, 1219, 1177, 1115, 1052

MS *m/z*, Found 213.1231 $[M\text{-}Br^-]^+$, Calcd. $C_{10}H_{17}N_2O_3$ 213.1239

MS *m/z*, 213.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

3-Methyl-1-(propoxyethoxycarbonylmethyl)imidazolium bromide (181a)



Yellow solid

The title compound was prepared from 1-methylimidazole (65.0 mmol, 5.33 g) and 2-propoxyethyl 2-bromoacetate (78.0 mmol, 17.55 g) according to the general procedure in 88 % yield (17.59 g, 57.3 mmol).

Molecular formula $C_{11}H_{19}BrN_2O_3$

Molecular weight 307 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.25 (s, 1H, *H2*), 7.48 (t, *J* = 1.8 Hz, 1H, *H4*), 7.35 (t, *J* = 1.8 Hz, 1H, *H3*), 5.46 (s, 2H, *H5*), 4.30 (t, *J* = 4.8 Hz, 2H, *H7*), 4.02 (s, 3H, *H1*), 3.61 (t, *J* = 4.8 Hz, 2H, *H8*), 3.37 (t, *J* = 6.8 Hz, 2H, *H9*), 1.54 (tq, *J* = 6.8, 7.5 Hz, 2H, *H10*), 0.85 (t, *J* = 7.5 Hz, 3H, *H11*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.12 (*C*O), 138.74 (N*C*H$_2$N), 123.68 (N*C*H$_2$), 122.77 (N*C*H$_2$), 73.08 (O*C*H$_2$-), 67.89 (N*C*H$_2$), 65.87 (N*C*H$_3$), 50.28 (O*C*H$_2$), 36.93 (O*C*H$_2$), 22.75 (*C*H$_2$), 10.50 (*C*H$_3$)

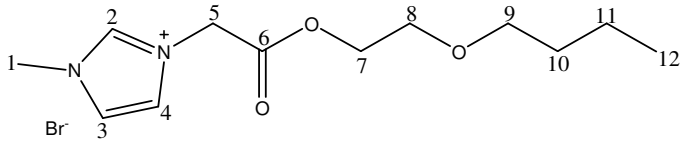
MP (°C) 25 – 27

IR (KBr disc) (cm^{-1}) 3099, 2967, 2927, 1751, 1578, 1568, 1558, 1539, 1495, 1452, 1216, 1176

MS *m/z*, Found 227.1410 [M-Br$^-$]$^+$, Calcd. $C_{11}H_{19}N_2O_3$ 227.1396

MS *m/z*, 227.1 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

3-Methyl-1-(butoxyethoxycarbonylmethyl)imidazolium bromide (182a)



Yellow solid

The title compound was prepared from 1-methylimidazole (160 mmol, 13.12 g) and 2-butoxyethyl 2-bromoacetate (190 mmol, 45.41 g) according to the general procedure in 89 % yield (45.69 g, 142 mmol).

Molecular formula $C_{12}H_{21}BrN_2O_3$

Molecular weight 321 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.19 (s, 1H, *H2*), 7.60 (t, *J* = 1.8 Hz, 1H, *H4*), 7.48 (t, *J* = 1.8 Hz, 1H, *H3*), 5.52 (s, 2H, *H5*), 4.36 (t, *J* = 4.6 Hz, 2H, *H7*), 4.10 (s, 3H, *H1*), 3.67 (t, *J* = 4.6 Hz, 2H, *H8*), 3.47 (t, *J* = 6.8 Hz, 2H, *H9*), 1.59 (tt, *J* = 6.8, 6.8 Hz, 2H, *H10*), 1.40 (tq, *J* = 6.8, 7.3 Hz, 2H, *H11*), 0.92 (t, *J* = 7.3 Hz, 3H, *H12*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.16 (*C*O), 138.54 (N*C*H$_2$N), 123.74 (N*C*H$_2$), 122.91 (N*C*H$_2$), 71.24 (O*C*H$_2$), 67.93 (N*C*H$_2$), 65.82 (N*C*H$_3$), 50.28 (O*C*H$_2$), 36.94 (O*C*H$_2$), 31.58 (*C*H$_2$), 19.22 (*C*H$_2$), 13.94 (*C*H$_3$)

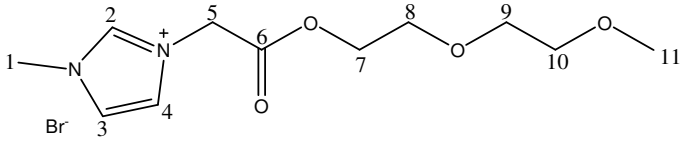
MP (°C) 28 – 30

IR (KBr disc) (cm^{-1}) 3094, 2957, 2933, 2866, 1751, 1575, 1569, 1558, 1539, 1495, 1452, 1216, 1177, 1120

MS *m/z*, Found 241.1539 [M-Br$^-$]$^+$, Calcd. $C_{12}H_{21}N_2O_3$ 241.1552

MS *m/z*, 241.1 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

3-Methyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium bromide (183a)



White solid

The title compound was prepared from 1-methylimidazole (100 mmol, 8.20 g) and 2-methoxy ethoxy ethyl 2-bromoacetate (120 mmol, 28.92 g) according to the general procedure in 97 % yield (31.49 g, 97.5 mmol).

Molecular formula $C_{11}H_{19}BrN_2O_4$

Molecular weight 323 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.21 (s, 1H, *H2*), 7.53 (t, *J* = 1.7 Hz, 1H, *H4*), 7.31 (t, *J* = 1.7 Hz, 1H, *H3*), 5.47 (s, 2H, *H6*), 4.32 (t, *J* = 4.6 Hz, 2H, *H7*), 4.02 (s, 3H, *H1*), 3.68 (t, *J* = 4.6 Hz, 2H, *H8*), 3.59 (t, *J* = 4.8 Hz, 2H, *H9*), 3.50 (t, *J* = 4.8 Hz, 2H, *H10*), 3.31 (s, 3H, *H11*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 164.38 (*C*O), 136.93 (N*C*H$_2$N), 122.06 (N*C*H$_2$), 120.93 (N*C*H$_2$), 70.00 (O*C*H$_2$), 68.69 (N*C*H$_2$), 66.75 (N*C*H$_3$), 63.87 (O*C*H$_2$), 57.24 (O*C*H$_2$), 48.49 (O*C*H$_2$), 35.13 (O*C*H$_3$)

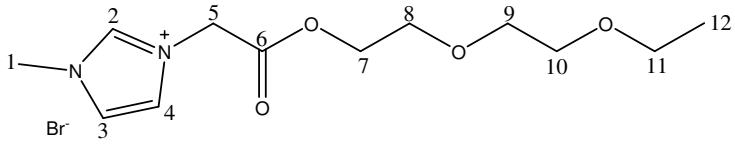
MP (°C) 52 – 54 ºC

IR (KBr disc) (cm^{-1}) 3437, 3157, 3101, 2925, 1749, 1496, 1452, 1398, 1217, 1177, 1102, 1049

MS *m/z*, Found 243.1333 $[M\text{-}Br^-]^+$, Calcd. $C_{11}H_{19}N_2O_4$ 243.1345

MS *m/z*, 243.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

3-Methyl-1-(ethoxyethoxyethoxycarbonylmethyl)imidazolium bromide (184a)



Pale yellow solid

The title compound was prepared from 1-methylimidazole (59.0 mmol, 4.84 g) and 2-ethoxy ethoxyethyl 2-bromoacetate (70.8 mmol, 18.05 g) according to the general procedure in 92 % yield (18.28 g, 54.2 mmol).

Molecular formula $C_{12}H_{21}BrN_2O_4$

Molecular weight 337 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.09 (s, 1H, *H2*), 7.61 (t, *J* = 1.8 Hz, 1H, *H4*), 7.41 (t, *J* = 1.8 Hz, 1H, *H3*), 5.46 (s, 2H, *H5*), 4.31 (t, *J* = 4.6 Hz, 2H, *H7*), 4.02 (s, 3H, *H1*), 3.68 (t, *J* = 4.6 Hz, 2H, *H8*), 3.59-3.57 (m, 2H, *H9*), 3.53-3.51 (m, 2H, *H10*), 3.49 (q, *J* = 7.1 Hz, 2H, *H11*), 1.13 (t, *J* = 7.1 Hz, 3H, *H12*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.24 (*C*O), 138.49 (N*C*H_2N), 123.93 (N*C*H_2), 122.87 (N*C*H_2), 70.65 (O*C*H_2), 69.70 (N*C*H_2), 68.55 (O*C*H_2), 66.66 (O*C*H_2), 65.64 (O*C*H_2), 50.27 (O*C*H_2), 36.92 (N*C*H_3), 15.18 (*C*H_3)

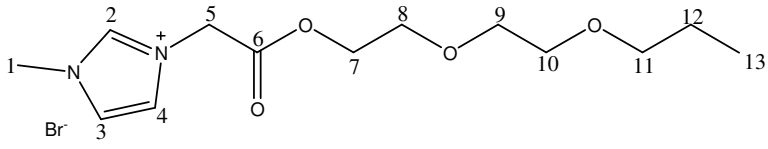
MP (°C) 28 – 30

IR (KBr disc) (cm^{-1}) 2026, 2862, 1751, 1568, 1558, 1539, 1495, 1451, 1217, 1175

MS *m/z*, Found 257.1498 $[M\text{-}Br^-]^+$, Calcd. $C_{12}H_{21}N_2O_4$ 257.1501

MS *m/z*, 257.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

3-Methyl-1-(propoxyethoxyethoxycarbonylmethyl)imidazolium bromide (185a)



White solid

The title compound was prepared from 1-methylimidazole (50.0 mmol, 4.10 g) and 2-propoxyethoxyethyl 2-bromoacetate (60.0 mmol, 16.14 g) according to the general procedure in 98 % yield (17.16 g, 48.89 mmol).

Molecular formula $C_{13}H_{23}BrN_2O_4$

Molecular weight 351 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.13 (s, 1H, *H2*), 7.54, (t, *J* = 1.8 Hz, 1H, *H4*), 7.34 (t, *J* = 1.8 Hz, 1H, *H3*), 5.45 (s, 2H, *H5*), 4.31 (t, *J* = 4.6 Hz, 2H, *H7*), 4.02 (s, 3H, *H1*), 3.68 (t, *J* = 4.6 Hz, 2H, *H8*), 3.59-3.57 (m, 2H, *H9*), 3.53-3.50 (m, 2H, *H10*), 3.35 (t, *J* = 6.9 Hz, 2H, *H11*), 1.53 (tq, *J* = 6.9, 7.3 Hz, 2H, *H12*), 0.84 (t, *J* = 7.3 Hz, 3H, *H13*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.21 (*C*O), 138.54 (N*C*H$_2$N), 123.85 (N*C*H$_2$), 122.84 (N*C*H$_2$), 73.10 (O*C*H$_2$), 70.62 (O*C*H$_2$), 69.92 (O*C*H$_2$), 68.55 (O*C*H$_2$), 65.69 (N*C*H$_2$), 50.29 (O*C*H$_2$), 36.93 (N*C*H$_3$), 22.76 (*C*H$_2$), 10.52 (*C*H$_3$)

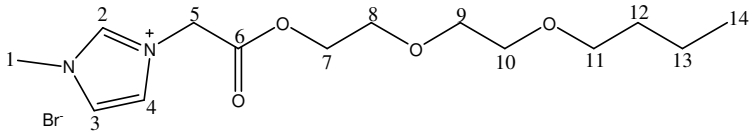
MP (°C) 32 – 34 ºC

IR (KBr disc) (cm^{-1}) 2959, 2926, 2859, 1751, 1558, 1639, 1495, 1452

MS *m/z*, Found 271.1648 [M-Br$^-$]$^+$, Calcd. $C_{13}H_{23}N_2O_4$ 271.1658

MS *m/z*, 271.2 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

3-Methyl-1-(butoxyethoxyethoxycarbonylmethyl)imidazolium bromide (186a)



White solid

The title compound was prepared from 1-methylimidazole (220 mmol, 18.04 g) and 2-butoxyethoxyethyl 2-bromoacetate (260 mmol, 73.58 g) according to the general procedure in 94 % yield (75.65 g, 207 mmol)

Molecular formula $C_{14}H_{25}BrN_2O_4$

Molecular weight 365 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.40 (s, 1H, *H2*), 7.37 (t, *J* = 1.6 Hz, 1H, *H4*), 7.19 (t, *J* = 1.6 Hz, 1H, *H3*), 5.42 (s, 2H, *H5*), 4.32 (t, *J* = 4.6 Hz, 2H, *H7*), 4.01 (s, 3H, *H1*), 3.69 (t, *J* = 4.6 Hz, 2H, *H8*), 3.59-3.56 (m, 2H, *H9*), 3.54-3.51 (m, 2H, *H10*), 3.40 (t, *J* = 6.8 Hz, 2H, *H11*), 1.50 (tt, *J* = 6.8 Hz, 7.2 Hz, 2H, *H12*), 1.30 (tq, *J* = 7.2 Hz, 7.3 Hz, 2H, *H13*), 0.85 (t, *J* = 7.3 Hz, 3H, *H14*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.23 (*C*O), 138.35 (N*C*H$_2$N), 123.97 (N*C*H$_2$), 123.03 (N*C*H$_2$), 71.20 (O*C*H$_2$), 70.60 (O*C*H$_2$), 69.94 (O*C*H$_2$), 68.54 (O*C*H$_2$), 65.66 (O*C*H$_2$), 50.27 (N*C*H$_2$), 36.96 (N*C*H$_3$), 31.62 (*C*H$_2$), 19.23 (*C*H$_2$), 13.94 (*C*H$_3$)

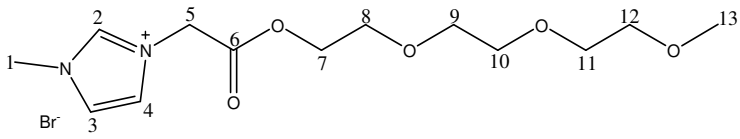
MP (°C) 48 – 50 ºC

IR (KBr disc) (cm^{-1}) 3445, 2927, 2861, 1553, 1494, 1453, 1086, 1051

MS *m/z*, Found 285.1803 [M-Br$^-$]$^+$, Calcd. $C_{14}H_{25}N_2O_4$ 285.1814

MS *m/z*, 285.2 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

3-Methyl-1-(methoxyethoxyethoxyethoxycarbonylmethyl)imidazolium bromide (187a)



Pale brown solid

The title compound was prepared from 1-methylimidazole (90.0 mmol, 7.38 g) and 2-(2-(2-methoxyethoxy)ethoxy)ethyl 2-bromoacetate (91.0 mmol, 25.94 g) according to the general procedure in 55 % yield (18.30 g, 49.86 mmol).

Molecular formula $C_{13}H_{23}BrN_2O_5$

Molecular weight 367 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.92 (s, 1H, *H2*), 7.45 (t, *J* = 1.6 Hz, 1H, *H4*), 7.60 (t, *J* = 1.6 Hz, 1H, *H3*), 5.47 (s, 2H, *H5*), 4.32 (t, *J* = 4.6 Hz, 2H, *H7*), 4.06 (s, 3H, *H1*), 3.70 (t, *J* = 4.6 Hz, 2H, *H8*), 3.61-3.58 (m, 6H, *H's 9-11*), 3.51-3.49 (m, 2H, *H12*), 3.31 (s, 3H, *H13*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.33 (*C*O), 138.18 (N*C*H_2N), 124.02 (N*C*H_2), 123.15 (N*C*H_2), 71.77 (O*C*H_2), 70.43 (O*C*H_2), 70.39 (O*C*H_2), 70.33 (O*C*H_2), 68.50 (O*C*H_2), 65.44 (O*C*H_2), 58.87 (O*C*H_3), 50.20 (N*C*H_2), 36.87 (N*C*H_3)

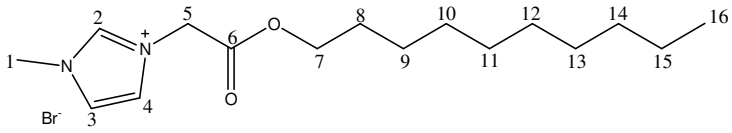
MP (°C) 59 – 61

IR (KBr disc) (cm^{-1}) 3150, 3095, 2925, 1751, 1635, 1575, 1569, 1558, 1494, 1451, 1216, 1176

MS *m/z*, Found 287.1605 $[M\text{-}Br^-]^+$, Calcd. $C_{13}H_{23}N_2O_5$ 287.1607

MS *m/z*, 287.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

3-Methyl-1-(decoxycarbonylmethyl)imidazolium bromide (188a)



White solid

The title compound was prepared from 1-methylimidazole (100 mmol, 8.20 g) and decyl 2-bromoacetate (110 mmol, 30.69 g) according to the general procedure in 51 % yield (18.47 g, 51.2 mmol).

Molecular formula $C_{16}H_{29}BrN_2O_2$

Molecular weight 361 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.36 (s, 1H, *H2*), 7.42 (t, *J* = 1.8 Hz, 1H, *H4*), 7.28 (t, *J* = 1.8 H, 1H, *H3*), 5.40 (s, 2H, *H5*), 4.14 (t, *J* = 6.8 Hz, 2H, *H7*), 4.02 (s, 3H, *H1*), 1.62-1.59 (m, 2H, *H8*), 1.23-1.18 (m, 14H, *H's 9-15*), 0.81 (t, *J* = 6.8 Hz, 3H, *H16*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.07 (*C*O), 138.93 (N*C*H$_2$N), 123.56 (N*C*H$_2$), 122.64 (N*C*H$_2$), 67.23 (O*C*H$_2$), 50.28 (N*C*H$_2$), 36.89 (N*C*H$_3$), 31.89 (*C*H$_2$), 29.54 (*C*H$_2$), 29.48 (*C*H$_2$), 29.31 (*C*H$_2$), 29.19 (*C*H$_2$), 28.35 (*C*H$_2$), 25.73 (*C*H$_2$), 22.70 (*C*H$_2$), 14.15 (*C*H$_3$)

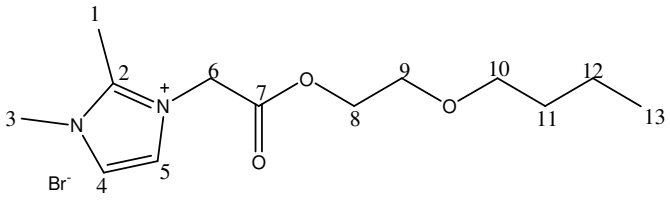
MP (°C) 49 – 51 ºC

IR (KBr disc) (cm^{-1}) 3426, 2961, 1919, 2853, 1748, 1232, 1178, 1052

MS *m/z*, Found 281.2228 [M-Br$^-$]$^+$, Calcd. $C_{16}H_{29}N_2O_2$ 281.2229

MS *m/z*, 281.2 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

2,3-Dimethyl-1-(butoxyethoxycarbonylmethyl)imidazolium bromide (190a)



Orange viscous liquid

The title compound was prepared from 1,2-dimethylimidazole (9.00 mmol, 0.86 g) and 2-butoxyethyl 2-bromoacetate (11.0 mmol, 2.63 g) according to the general procedure in 92 % yield (2.78 g, 8.30 mmol).

Molecular formula $C_{13}H_{23}BrN_2O_3$

Molecular weight 335 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.81 (d, *J* = 2.4 Hz, 1H, *H5*), 7.53 (d, *J* = 2.4 Hz, 1H, *H4*), 5.42 (s, 2H, *H6*), 4.30 (t, *J* = 4.6 Hz, 2H, *H8*), 3.89 (s, 3H, *H3*), 3.61 (t, *J* = 4.6 Hz, 2H, *H9*), 3.47 (t, *J* = 6.7 Hz, 2H, *H10*), 2.56 (s, 3H, *H1*), 1.56 (tt, *J* = 6.7, 7.2 Hz, 2H, *H11*), 1.36 (tq, *J* = 7.2, 7.5 Hz, 2H, *H12*), 0.93 (t, *J* = 7.5 Hz, 3H, *H13*)

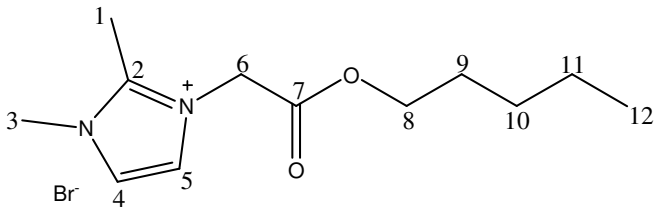
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.30 (*C*O), 145.78 (N*C*HN), 123.02 (N*C*H_2), 122.34 (N*C*H_2), 71.24 (O*C*H_2), 67.98 (O*C*H_2), 65.69 (O*C*H_2), 50.02 (N*C*H_2), 36.04 (N*C*H_3), 31.62 (*C*H_2), 19.04 (*C*H_2), 13.96 (N*C*H_3), 11.27 (*C*H_3)

IR (thin film on salt plate) (cm^{-1}) 2957, 2933, 2866, 1751, 1593, 1558, 1546, 1495, 1451, 1216, 1120

MS *m/z*, Found 255.1689 $[M\text{-}Br^-]^+$, Calcd. $C_{13}H_{23}N_2O_3$ 255.1709

MS *m/z*, 255.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

2,3-Dimethyl-1-(pentoxycarbonylmethyl)imidazolium bromide (189a)



Orange viscous liquid

The title compound was prepared from 1,2-dimethylimidazole (150 mmol, 14.40 g) and pentyl 2-bromoacetate (168 mmol, 35.11 g) according to the general procedure in 81 % yield (36.91 g, 121 mmol)

Molecular formula $C_{12}H_{21}BrN_2O_2$

Molecular weight 305 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.74 (d, *J* = 2.0 Hz, 1H, *H5*), 7.46 (d, *J* = 2.0 Hz, 1H, *H4*), 5.38 (s, 2H, *H6*), 4.13 (t, *J* = 6.8 Hz, 2H, *H8*), 3.89 (s, 3H, *H3*), 2.69 (s, 3H, *H1*), 1.63-1.54 (m, 2H, *H9*), 1.27-1.20 (m, 4H, *H's 10 and 11*), 0.85 (t, *J* = 7.0 Hz, 3H, *H12*)

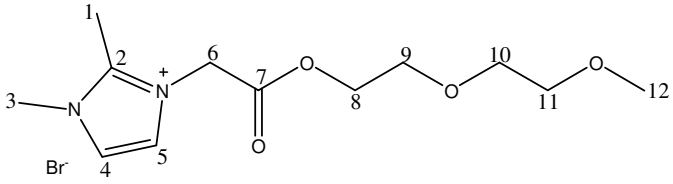
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.31 (*C*O), 145.81 (N*C*HN), 122.98 (N*C*H_2), 122.22 (N*C*H_2), 67.08 (O*C*H_2), 50.12 (N*C*H_2), 36.03 (N*C*H_3), 28.06 (*C*H_2), 27.83 (*C*H_2), 22.24 (*C*H_2), 13.95 (*C*H_2), 11.35 (N*C*H_3)

IR (thin film on salt plate) (cm^{-1}) 2957, 2928, 2858, 1751, 1558, 1545, 1539, 1495, 1452, 1238, 1210, 1176

MS *m/z*, Found 225.1594 $[M\text{-}Br^-]^+$, Calcd. $C_{12}H_{21}N_2O_2$ 225.1603

MS *m/z*, 225.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

2,3-Dimethyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium bromide (191a)



White powder

The title compound was prepared from 1,2-dimethylimidazole (150 mmol, 14.40 g) and 2-(2-methoxyethoxy) ethyl 2-bromoacetate (171 mmol, 41.21 g) according to the general procedure in 88 % yield (44.48 g, 132 mmol).

Molecular formula $C_{12}H_{21}BrN_2O_4$

Molecular weight 337 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.69 (d, *J* = 2.0 Hz, 1H, *H5*), 7.34 (d, *J* = 2.0 Hz, 1H, *H4*), 5.40 (s, 2H, *H6*), 4.32 (t, *J* = 4.7 Hz, 2H, *H8*), 3.86 (s, 3H, *H3*), 3.68 (t, *J* = 4.7 Hz, 2H, *H9*), 3.59 (t, *J* = 4.4 Hz, 2H, *H10*), 3.49 (t, *J* = 4.4 Hz, 2H, *H11*), 3.31 (s, 3H, *H1*), 2.71 (s, 3H, *H12*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.34 (*C*O), 145.77 (N*C*HN), 123.04 (N*C*H_2), 122.38 (N*C*H_2), 71.79 (O*C*H_2), 70.47 (O*C*H_2), 68.55 (O*C*H_2), 65.51 (O*C*H_2), 59.02 (O*C*H_3), 49.96 (N*C*H_2), 35.98 (N*C*H_3), 11.25 (N*C*H_3)

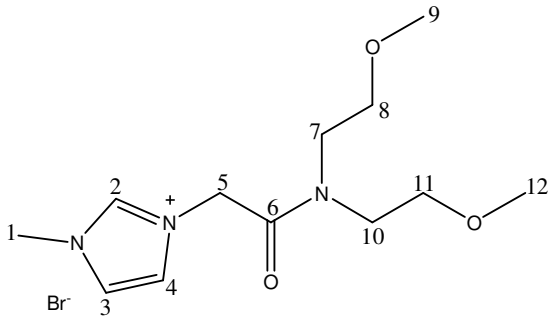
MP (°C) 74 – 75

IR (KBr disc) (cm^{-1}) 3426, 2925, 2868, 1747, 1453, 1248, 1214, 1135, 1099, 1026

MS *m/z*, Found 257.1492 $[M\text{-}Br^-]^+$, Calcd. $C_{12}H_{21}N_2O_4$ 257.1501

MS *m/z*, 257.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

3-Methyl-1-[(*bis*-1-methoxyethyl)carbamylmethyl]imidazolium bromide (205a)



The title compound was prepared from 1-methylimidazole (45.0 mmol, 3.69 g) and 2-bromo-*N*,*N*-bis-(2-methoxy ethyl) acetamide (50.0 mmol, 12.70 g) according to the general procedure in 91 % yield (13.76 g, 41.0 mmol).

White powder

Molecular formula $C_{12}H_{22}BrN_3O_3$

Molecular weight 336 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.91 (s, 1H, *H2*), 7.44 (t, *J* = 1.8 Hz, 1H, *H4*), 7.42 (t, *J* = 1.8 Hz, 1H, *H3*), 5.66 (s, 2H, *H5*), 4.07 (s, 3H, *H1*), 3.70 (t, *J* = 4.8 Hz, 2H, *H7*), 3.57-3.55 (m, 4H, *H's 8 and 11*), 3.50-3.47(m, 2H, *H10*), 3.36 (s, 3H, *H9*), 3.31 (s, 3H, *H12*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.46 (*C*O), 138.30 (N*C*H_2N), 124.14 (N*C*H_2), 122.31 (N*C*H_2), 70.51 (O*C*H_2), 70.05 (O*C*H_2), 59.25 (O*C*H_3), 58.92 (O*C*H_3), 50.63 (N*C*H_2), 48.82 (N*C*H_2), 46.83 (N*C*H_2), 36.75 (N*C*H_3)

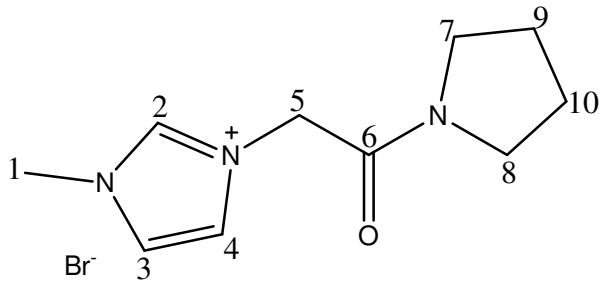
MP (°C) 68 – 70

IR (KBr disc) (cm^{-1}) 3441, 3108, 2940, 1654, 1576, 1474, 1427, 1178, 1116, 1015

MS *m/z*, Found 256.1653 $[M\text{-}Br^-]^+$, Calcd. $C_{12}H_{22}N_3O_3$ 256.1661

MS *m/z*, 256.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

3-Methyl-1-(pyrrolidinylcarbonylmethyl)imidazolium bromide (197a)



White powder

The title compound was prepared from 1-methylimidazole (36.0 mmol, 2.95 g) and 2-bromo-1-(pyrrolidin-1-yl) ethanone (39.0 mmol, 7.49 g) according to the general procedure in 56 % yield (5.52 g, 20.15 mmol).

Molecular formula $C_{10}H_{16}BrN_3O$

Molecular weight 274 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.80 (s, 1H, *H2*), 7.71 (t, *J* = 1.8 Hz, 1H, *H4*), 7.46 (t, *J* = 1.8 Hz, 1H, *H3*), 5.58 (s, 2H, *H5*), 4.02 (s, 3H, *H1*), 3.65 (t, *J* = 6.8 Hz, 2H, *H7*), 3.42 (t, *J* = 6.8 Hz, 2H, *H8*), 2.04 (tt, *J* = 6.8, 7.2 Hz, 2H, *H9*), 1.86 (tt, *J* = 6.8, 7.2 Hz, 2H, *H10*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 162.63 (*C*O), 137.95 (N*C*H$_2$N), 124.41 (N*C*H$_2$), 122.32 (N*C*H$_2$), 51.09 (N*C*H$_2$), 46.55 (N*C*H$_2$), 46.11 (N*C*H$_2$), 36.76 (N*C*H$_3$), 25.98 (*C*H$_2$), 24.04 (*C*H$_2$)

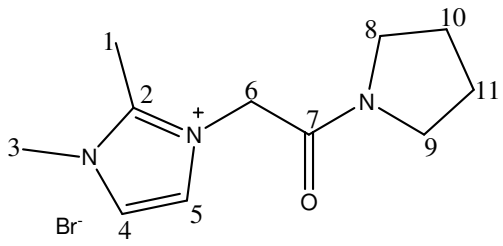
MP (°C) 109 – 111

IR (KBr disc) (cm^{-1}) 3443, 1656, 1573, 1424, 1343, 1176, 1042

MS *m/z*, 194.1289 [M-Br$^-$]$^+$, Calcd. $C_{10}H_{16}N_3O$ 194.1293

MS *m/z*, 194.1 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

2,3-Dimethyl-1-(pyrrolidinylcarbonylmethyl)imidazolium bromide (198a)



White powder

The title compound was prepared from 1,2-dimethylimidazole (40.0 mmol, 3.84 g) and 2-bromo-1-(pyrrolidin-1-yl) ethanone (42.0 mmol, 8.06 g) according to the general procedure in 82 % yield (9.41 g, 32.8 mmol).

Molecular formula $C_{11}H_{18}BrN_3O$

Molecular weight 288 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.84 (d, *J* = 2.2 Hz, 1H, *H5*), 7.47 (d, *J* = 2.2 Hz, 1H, *H4*), 5.66 (s, 2H, *H6*), 3.91 (s, 3H, *H3*), 3.76 (t, *J* = 6.8 Hz, 2H, *H8*), 3.46 (t, *J* = 6.8 Hz, 2H, *H9*), 2.72 (s, 3H, *H1*), 2.05 (tt, *J* = 6.8, 6.4 Hz, 2H, *H10*), 1.92 (tt, *J* = 6.8, 6.4 Hz, 2H, *H11*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 162.51 (*C*O), 146.06 (N*C*HN), 123.04 (N*C*H_2), 121.70 (N*C*H_2), 51.16 (N*C*H_2), 46.50 (N*C*H_2), 46.18 (N*C*H_2), 35.80 (N*C*H_3), 26.01 (N*C*H_3), 24.05 (*C*H_2), 11.15 (*C*H_2-)

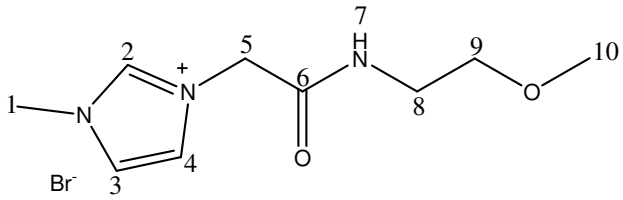
MP (°C) 142 – 144

IR (KBr disc) (cm^{-1}) 3406, 3141, 1646, 1478, 1420, 1337, 1165

MS *m/z*, 208.1441 $[M\text{-}Br^-]^+$, Calcd. $C_{11}H_{18}N_3O$ 208.1450

MS *m/z*, 208.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

3-Methyl-1-(methoxyethylcarbamylmethyl)imidazolium bromide (203a)



Yellow viscous liquid

The title compound was prepared from 1-methylimidazole (50.0 mmol, 4.10 g) and 2-bromo-*N*- (2-methoxyethyl) acetamide (56.0 mmol, 10.98 g) according to the general procedure in 97 % yield (13.48 g, 48.5 mmol).

Molecular formula $C_9H_{16}BrN_3O_2$

Molecular weight 278 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.76 (s, 1H, *H2*), 8.55 (t, *J* = 5.2 Hz, 1H, *H7*), 7.65 (t, *J* = 1.6 Hz, 1H, *H4*), 7.31 (t, *J* = 1.6 Hz, 1H, *H3*), 5.39 (s, 2H, *H5*), 4.05 (s, 3H, *H1*), 3.56-3.53 (m, 2H, *H8*), 3.48-3.44 (m, 2H, *H9*), 3.36 (s, 3H, *H10*)

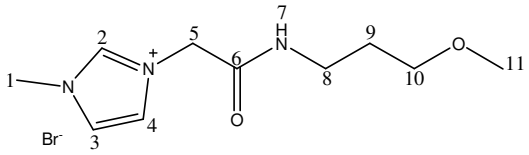
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 164.74 (*C*O), 137.73 (N*C*H_2N), 123.90 (N*C*H_2), 122.44 (N*C*H_2), 70.40 (O*C*H_2), 58.69 (O*C*H_3), 51.75 (N*C*H_2), 39.51 (N*C*H_3), 36.80 (N*C*H_2)

IR (thin film on salt plate) (cm^{-1}) 3064, 1683, 1559, 1456, 1261, 1177, 1122, 1022

MS *m/z*, 198.1238 $[M\text{-}Br^-]^+$, Calcd. $C_9H_{16}N_3O_2$ 198.1243

MS *m/z*, 198.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

3-Methyl-1-(methoxypropylcarbamylmethyl)imidazolium bromide (204a)



Beige solid

The title compound was prepared from 1-methylimidazole (43.0 mmol, 3.53 g) and 2-bromo-*N*-(3-methoxypropyl) acetamide (46.0 mmol, 9.66 g) according to the general procedure in 91 % yield (11.43 g, 39.1 mmol).

Molecular formula $C_{10}H_{18}BrN_3O_2$

Molecular weight 292 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.66 (s, 1H, *H2*), 8.53 (t, *J* = 5.4 Hz, 1H, *H7*), 7.65 (t, *J* = 1.8 Hz, 1H, *H4*), 7.41 (t, *J* = 1.8 Hz, 1H, *H3*), 5.33 (s, 2H, *H5*), 4.04 (s, 3H, *H1*), 3.42 (t, *J* = 6.3 Hz, 2H, *H8*), 3.34-3.26 (m, 5H, *H's 10 and 11*), 1.83 (tt, *J* = 6.3, 6.8 Hz, 2H, *H9*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 164.43 (*C*O), 137.49 (N*C*H$_2$N), 123.77 (N*C*H$_2$), 122.76 (N*C*H$_2$), 70.16 (O*C*H$_2$), 58.62 (O*C*H$_3$), 51.73 (N*C*H$_2$), 37.25 (N*C*H$_2$), 36.83 (N*C*H$_3$), 29.08 (*C*H$_2$)

MP (°C) 75 – 77

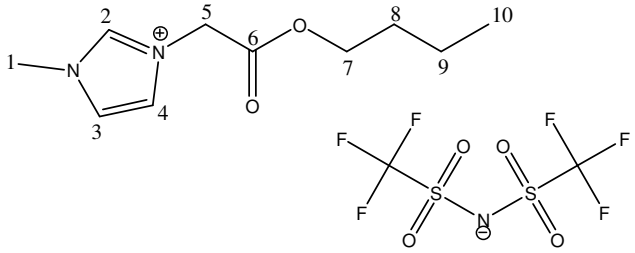
IR (KBr disc) (cm^{-1}) 3440, 3081, 2939, 1684, 1567, 1447, 1264, 1178, 1112

MS *m/z*, 212.1395 [M-Br$^-$]$^+$, Calcd. $C_{10}H_{18}N_3O_2$ 212.1399

MS *m/z*, 212.1 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

Achiral NTf_2 salts

Representative method for the preparation of NTf_2 salts (3-methyl-1-(butoxycarbonylmethyl)imidazolium NTf_2) (177d)



A flask was charged with 3-methyl-1-(butoxy carbonylmethyl) imidazolium bromide **177a** (3.05 g, 11.0 mmol) and distilled water (10 mL). $LiNTf_2$ (4.89 g, 17.0 mmol) in distilled water (3 mL) was added in one portion and the suspension was stirred vigorously for 6 h at RT. The top aqueous layer was removed and the IL was washed with distilled water (3 x 10 mL). The solvent was then removed on the rotary evaporator and the product was dried under high vacuum for 3 h to give a pale yellow oil in 86 % yield (4.49 g, 9.41 mmol).

Molecular formula $C_{12}H_{17}F_6N_3O_6S_2$

Molecular weight 477 g/mol

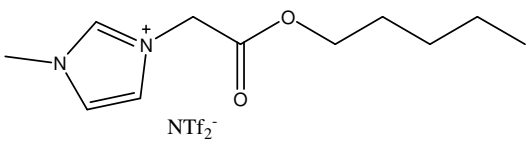
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.78 (s, 1H, *H2*), 7.30 (t, *J* = 1.8 Hz, 1H, *H4*), 7.24 (t, *J* = 1.8 Hz, 1H, *H3*), 4.95 (s, 2H, *H5*), 4.15 (t, *J* = 6.7 Hz, 2H, *H7*), 3.89 (s, 3H, *H1*), 1.59 (tt, *J* = 6.7, 7.4 Hz, 2H, *H8*), 1.31 (tq, *J* = 7.4, 7.2 Hz, 2H, *H9*), 0.87 (t, *J* = 7.2 Hz, 3H, *H10*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.75 (*C*OO), 137.69 (N*C*HN), 123.79 (N*C*H_2), 123.16 (N*C*H_2), 122.03 (q, *J* = 320 Hz, 2*C*F_3's), 66.97 (O*C*H_2-), 49.93 (N*C*H_2), 36.56 (*C*H_2), 30.03 (*C*H_2), 18.87 (*C*H_2), 13.55 (*C*H_3)

IR (thin film on salt plate) (cm^{-1}) 3164, 3125, 2966, 2937, 2876, 1750, 1580, 1569, 1559, 1495, 1457, 1354, 1197, 1136

MS *m/z*, 197.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(pentoxycarbonylmethyl)imidazolium NTf_2 (178d)



Yellow slightly viscous oil

The title compound was prepared from 3-methyl-1-(pentoxy carbonyl methyl) imidazolium bromide **178a** (19.15 g, 39.0 mmol) and $LiNTf_2$ (13.49 g, 47.0 mmol) according to the general procedure in 93 % yield (17.78 g, 36.2 mmol).

Molecular formula $C_{13}H_{19}F_6N_3O_2S_2$

Molecular weight 491 g/mol

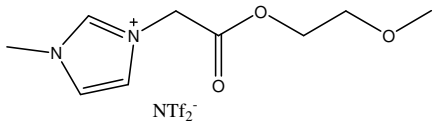
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.67 (s, 1H), 7.32 (t, *J* = 1.6 Hz, 1H), 7.27 (t, *J* = 1.6 Hz, 1H), 4.91 (s, 2H), 4.11 (t, *J* = 6.8 Hz, 2H), 3.85 (s, 3H), 1.65-1.57 (m, 2H), 1.24-1.23 (m, 4H), 0.82 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.76, 137.52, 123.85, 123.25, 122.20 (q, *J* = 319 Hz, 2*C*F_3's), 67.20, 49.88, 36.48, 27.91, 27.73, 22.18, 13.82

IR (thin film on salt plate) (cm^{-1}) 3164, 3124, 2963, 2928, 2862, 1750, 1582, 1569, 1558, 1495, 1455, 1354, 1197, 1136

MS *m/z*, 211.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(methoxyethoxycarbonylmethyl)imidazolium NTf_2 (179d)



Pale brown viscous liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxyoxy carbonylmethyl) imidazolium bromide **179a** (1.74 g, 6.26 mmol) and $LiNTf_2$ (2.16 g, 7.51 mmol) according to the general procedure in 91 % yield (2.73 g, 5.70 mmol).

Molecular formula $C_{11}H_{15}F_6N_3O_7S_2$

Molecular weight 479 g/mol

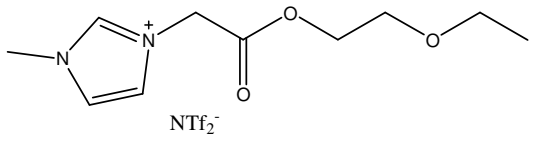
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.85 (s, 1H), 7.39 (t, *J* = 1.8 Hz, 1H), 7.33 (t, *J* = 1.8 Hz, 1H), 5.07 (s, 2H), 4.40 (t, *J* = 4.6 Hz, 2H), 3.98 (s, 3H), 3.66 (t, *J* = 4.6 Hz, 2H), 3.40 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.73, 137.75, 123.78, 123.18, 119.70 (q, J = 319 Hz, 2*C*F_3's), 69.75, 65.72, 63.24, 58.89, 49.93

IR (thin film on salt plate) (cm^{-1}) 2926, 2855, 1750, 1636, 1558, 1539, 1495, 1452, 1365, 1204, 1129

MS *m/z*, 199.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(ethoxyethoxycarbonylmethyl)imidazolium NTf_2 (180d)



Orange liquid

The title compound was prepared from 3-methyl-1-(ethoxy ethoxy carbonyl methyl) imidazolium bromide **180a** (2.93 g, 10.0 mmol) and $LiNTf_2$ (4.59 g, 16.0 mmol) according to the general procedure in 90 % yield (4.42 g, 8.97 mmol).

Molecular formula $C_{12}H_{17}F_6N_3O_7S_2$

Molecular weight 493 g/mol

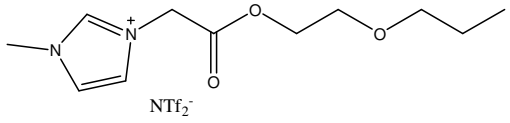
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.82 (s, 1H), 7.39 (t, *J* = 1.8 Hz, 1H), 7.34 (t, *J* = 1.8 Hz, 1H), 5.06 (s, 2H), 4.38 (t, *J* = 4.6 Hz, 2H), 3.97 (s, 3H), 3.68 (t, *J* = 4.6 Hz, 2H), 3.56 (q, *J* = 7.1 Hz, 2H), 1.22 (t, *J* = 7.1 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.76, 137.63, 123.80, 123.25, 119.70 (q, *J* = 319 Hz, 2*C*F_3's), 67.62, 66.67, 65.97, 49.92, 36.56, 15.01

IR (thin film on salt plate) (cm^{-1}) 3169, 3116, 2967, 2927, 2859, 1751, 1581, 1569, 1558, 1495, 1452, 1352, 1196, 1135

MS *m/z*, 213.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(propoxyethoxycarbonylmethyl)imidazolium NTf_2 (181d)



Slightly viscous yellow oil

The title compound was prepared from 3-methyl-1-(propoxy ethoxy carbonyl methyl) imidazolium bromide **181a** (3.55 g, 7.00 mmol) and $LiNTf_2$ (2.15 g, 7.50 mmol) according to the general procedure in 68 % yield (2.43 g, 4.79 mmol).

Molecular formula $C_{13}H_{19}F_6N_3O_7S_2$

Molecular weight 507 g/mol

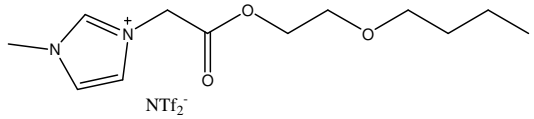
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.78 (s, 1H), 7.39 (t, *J* = 1.8 Hz, 1H), 7.36 (t, *J* = 1.8 Hz, 1H), 5.04 (s, 2H), 4.37 (t, *J* = 4.8 Hz, 2H), 3.95 (s, 3H), 3.67 (t, *J* = 4.8 Hz, 2H), 3.43 (t, *J* = 6.7 Hz, 2H), 1.61 (tq, *J* = 6.7, 7.3 Hz, 2H), 0.92 (t, *J* = 7.3 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.76, 137.50, 123.82, 123.34, 119.09 (q, *J* = 319 Hz, 2*C*F_3's), 72.99, 67.79, 65.91, 49.87, 56.49, 22.68, 10.37

IR (thin film on salt plate) (cm^{-1}) 3164, 3117, 2968, 2927, 2862, 1751, 1569, 1558, 1539, 1495, 1452, 1353, 1198, 1135

MS *m/z*, 227.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(butoxyethoxycarbonylmethyl)imidazolium NTf_2 (182d)



Pale yellow oil

The title compound was prepared from 3-methyl-1-(butoxy ethoxy carbonyl methyl) imidazolium bromide **182a** (1.85 g, 5.77 mmol) and $LiNTf_2$ (1.99 g, 6.92 mmol) according to the general procedure in 84 % yield (2.73 g, 4.82 mmol).

Molecular formula $C_{14}H_{21}F_6N_3O_7S_2$

Molecular weight 521 g/mol

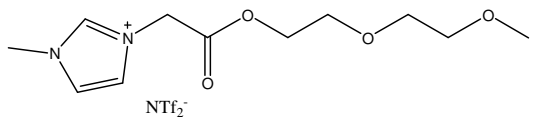
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.71 (s, 1H), 7.38 (t, *J* = 1.8 Hz, 1H), 7.36 (t, *J* = 1.8 Hz, 1H), 5.00 (s, 2H), 4.32 (t, *J* = 4.8 Hz, 2H), 3.91 (s, 3H), 3.64 (t, *J* = 4.8 Hz, 2H), 3.44 (t, *J* = 6.7 Hz, 2H), 1.54 (tt, *J* = 6.7, 7.2 Hz, 2H), 1.34 (tq, *J* = 7.2, 7.5 Hz, 2H), 0.89 (t, *J* = 7.5 Hz, 3 H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.78, 137.32, 123.83, 123.40, 122.33 (q, *J* = 319 Hz, 2*C*F_3's), 71.09, 67.78, 65.81, 49.78, 36.37, 31.50, 19.11, 13.78

IR (thin film on salt plate) (cm^{-1}) 3164, 3123, 2959, 2934, 2864, 1756, 1582, 1569, 1558, 1495, 1453, 1354, 1197, 1135

MS *m/z*, 241.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium NTf_2 (183d)



Yellow oil

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **183a** (1.01 g, 3.13 mmol) and $LiNTf_2$ (1.09 g, 3.80 mmol) according to the general procedure in 91 % yield (1.49 g, 2.85 mmol).

Molecular formula $C_{13}H_{19}F_6N_3O_8S_2$

Molecular weight 523 g/mol

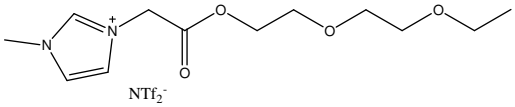
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.80 (s, 1H), 7.42 (t, *J* = 1.8 Hz, 1H), 7.36 (t, *J* = 1.8 Hz, 1H), 5.05 (s, 2H), 4.38 (t, *J* = 4.7 Hz, 2H), 3.96 (s, 3H), 3.74 (t, *J* = 4.7 Hz, 2H), 3.65-3.60 (m, 2H), 3.56-3.53 (m, 2H), 3.37 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.81, 137.55, 123.89, 123.28, 119.15 (q, *J* = 319 Hz, 2*C*F_3's), 71.69, 70.35, 68.38, 65.65, 58.88, 49.86, 36.48

IR (thin film on salt plate) (cm^{-1}) 3162, 3123, 2962, 2926, 2861, 1751, 1580, 1569, 1558, 1495, 1452, 1354, 1198, 1136

MS *m/z*, 243.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(ethoxyethoxyethoxycarbonylmethyl)imidazolium NTf_2 (184d)



Yellow slightly viscous liquid

The title compound was prepared from 3-methyl-1-(ethoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **183a** (1.88 g, 5.59 mmol) and $LiNTf_2$ (1.92 g, 6.70 mmol) according to the general procedure in 87 % yield (2.61g, 4.86 mmol).

Molecular formula $C_{14}H_{21}F_6N_3O_8S_2$

Molecular weight 537 g/mol

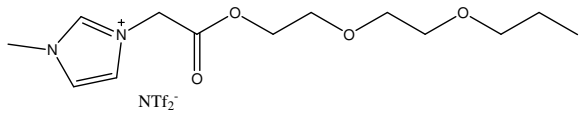
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.82 (s, 1H), 7.42 (t, *J* = 1.8 Hz, 1H), 7.35 (t, *J* = 1.8 Hz, 1H), 5.05 (s, 2H), 4.38 (t, *J* = 4.8 Hz, 2H), 3.97 (s, 3H), 3.74 (t, *J* = 4.8 Hz, 2H), 3.66 (t, *J* = 4.4 Hz, 2H), 3.61 (t, *J* = 4.4 Hz, 2H), 3.58 (q, *J* = 7.0 Hz, 2H), 1.21 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.79, 137.59, 123.90, 123.27, 119.69 (q, *J* = 319 Hz, 2*C*F_3's), 70.56, 69.61, 68.40, 66.62, 65.71, 49.89, 36.52, 15.09

IR (thin film on salt plate) (cm^{-1}) 3162, 3123, 2969, 2926, 2865, 1752, 1582, 1558, 1495, 1452, 1354, 1197, 1135

MS *m/z*, 257.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(propoxyethoxyethoxycarbonylmethyl)imidazolium NTf_2 (185d)



Slightly viscous yellow liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **185a** (1.91 g, 5.45 mmol) and $LiNTf_2$ (1.88 g, 6.54 mmol) according to the general procedure in 82 % yield (2.46 g, 4.46 mmol).

Molecular formula $C_{15}H_{23}F_6N_3O_8S_2$

Molecular weight 551 g/mol

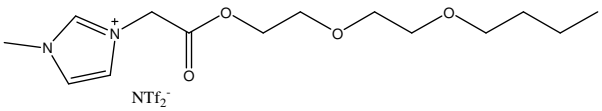
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.92 (s, 1H), 7.40 (t, *J* = 1.7 Hz, 1H), 7.31 (t, *J* = 1.7 Hz, 1H), 5.08 (s, 2H), 4.41 (t, *J* = 4.8 Hz, 2H), 4.00, (s, 3H), 3.77 (t, *J* = 4.8 Hz, 2H), 3.67 (t, *J* = 4.8, 2H), 3.61 (t, *J* = 4.8 Hz, 2H), 3.44 (t, *J* = 6.8 Hz, 2H), 1.61 (tq, *J* = 6.8, 7.2 Hz, 2H), 0.93 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.71, 137.92, 123.80, 123.07, 122.00 (q, *J* = 319 Hz, 2*C*F_3's), 73.09, 70.58, 69.89, 68.42, 65.86, 50.02, 36.66, 22.76, 10.47

IR (thin film on salt plate) (cm^{-1}) 3164, 3119, 2966, 2927, 2865, 1751, 1568, 1558, 1495, 1452, 1353, 1198, 1135

MS *m/z*, 271.3 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(butoxyethoxyethoxycarbonylmethyl)imidazolium NTf_2 (186d)



Slightly viscous yellow liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxycarbonylmethyl) imidazolium bromide **186a** (2.34 g, 6.40 mmol) and $LiNTf_2$ (2.20 g, 7.68 mmol) according to the general procedure in 86 % yield (3.10 g, 5.48 mmol).

Molecular formula $C_{16}H_{25}F_6N_3O_8S_2$

Molecular weight 555 g/mol

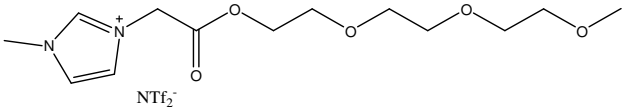
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.73 (s, 1H), 7.34 (t, *J* = 1.6 Hz, 1H), 7.27 (t, *J* = 1.6 Hz, 1H), 4.96 (s, 2H), 4.31 (t, *J* = 4.8 Hz, 2H), 3.88 (s, 3H), 3.67 (t, *J* = 4.8 Hz, 2H), 3.56-3.55 (m, 2H), 3.52-3.49 (m, 2H), 3.40 (t, *J* = 6.8 Hz, 2H), 1.51 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.33 (tq, *J* = 7.2, 7.3 Hz, 2H), 0.86 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.74, 137.60, 123.88, 123.28, 119.71 (q, *J* = 319 Hz, 2*C*F_3's), 71.17, 70.54, 69.90, 68.39, 65.75, 49.90, 36.52, 31.62, 19.95, 13.87

IR (thin film on salt plate) (cm^{-1}) 3163, 3123, 2957, 2934, 2868, 1756, 1569, 1558, 1539, 1495, 1455, 1354, 1197, 1135

MS *m/z*, 285.3 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(methoxyethoxyethoxyethoxycarbonylmethyl)imidazolium NTf_2 (187d)



Brown liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **187a** (2.20 g, 6.00 mmol) and $LiNTf_2$ (2.01 g, 7.00 mmol) according to the general procedure in 93 % yield (3.17 g, 5.60 mmol).

Molecular formula $C_{15}H_{23}F_6N_3O_9S_2$

Molecular weight 567 g/mol

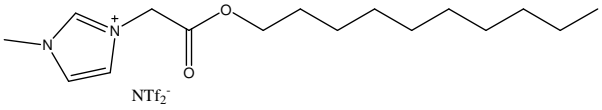
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.78 (s, 1H), 7.37 (t, *J* = 1.6 Hz, 1H), 7.26 (t, *J* = 1.6 Hz, 1H), 4.99 (s, 2H), 4.31 (t, *J* = 4.6 Hz, 2H), 3.89 (s, 3H), 3.66 (t, *J* = 4.6 Hz, 2H), 3.57-3.54 (m, 6H), 3.49-3.47 (m, 2H), 3.28 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.78, 137.75, 123.96, 123.18, 119.7 (q, *J* = 319 Hz, 2*C*F_3's), 71.79, 70.42, 70.38, 70.32, 68.35, 65.57, 58.82, 49.92, 36.53

IR (thin film on salt plate) (cm^{-1}) 3161, 3116, 2925, 2859, 1751, 1569, 1558, 1539, 1495, 1452, 1354, 1198, 1135

MS *m/z*, 287.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

3-Methyl-1-(decoxycarbonylmethyl)imidazolium NTf_2 (188d)



Yellow oil

The title compound was prepared from 3-methyl-1-(decoxy carbonyl methyl) imidazolium bromide **188a** (3.03 g, 8.40 mmol) and $LiNTf_2$ (2.73 g, 9.51 mmol) according to the general procedure in 95 % (4.46 g, 7.94 mmol).

Molecular formula $C_{18}H_{29}F_6N_3O_6S_2$

Molecular weight 561 g/mol

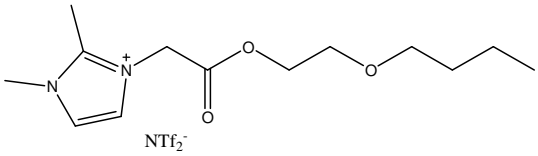
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.76 (s, 1H), 7.30 (t, *J* = 1.6 Hz, 1H), 7.24 (t, *J* = 1.6 Hz, 1H), 4.94 (s, 2H), 4.16 (t, *J* = 7.0 Hz, 2H), 3.89 (s, 3H), 1.63-1.55 (m, 2H), 1.24-1.95 (m, 14H), 0.83 (t, *J* = 6.8 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.75, 137.54, 123.83, 123.26, 119.71 (q, J = 319 Hz, 2*C*F_3's), 67.24, 49.89, 36.49, 29.62, 29.56, 29.51, 29.44, 29.29, 28.24, 25.74, 22.67, 14.10

IR (thin film on salt plate) (cm^{-1}) 3171,3120, 2957, 2926, 2859, 1751, 1558, 1539, 1497, 1452, 1354, 1198, 1134

MS *m/z*, 281.3 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

2,3-Dimethyl-1-(butoxyethoxycarbonylmethyl)imidazolium NTf_2 (190d)



Brown liquid

The title compound was prepared from 2,3-dimethyl-1-(butoxy carbonyl methyl) imidazolium bromide **190a** (3.69 g, 11.0 mmol) and $LiNTf_2$ (4.59 g, 16.0 mmol) according to the general procedure in 83 % yield (4.88 g, 9.12 mmol).

Molecular formula $C_{15}H_{23}F_6N_3O_7S_2$

Molecular weight 535 g/mol

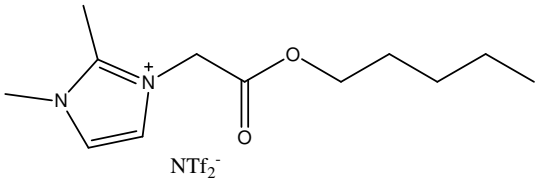
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.26 (dd, *J* = 1.8, 1.8 Hz, 2H), 4.95 (s, 2H), 4.37 (t, *J* = 4.6 Hz, 2H), 3.83 (s, 3H), 3.67 (t, *J* = 4.6 Hz, 2H), 3.48 (t, *J* = 6.7 Hz, 2H), 1.57 (tt, *J* = 6.7, 7.2 Hz, 2H), 1.36 (tq, *J* = 7.2, 7.5 Hz, 2H), 0.93 (t, *J* = 7.5 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.72, 145.53, 122.39, 122.36, 119.7 (q, *J* = 320 Hz, 2*C*F_3's), 71.16, 67.83, 65.87, 49.16, 35.50, 31.56, 19.18, 13.86, 9.74

IR (thin film on salt plate) (cm^{-1}) 3151, 2962, 2934, 2865, 1751, 1595, 1558, 1539, 1495, 1452, 1352, 1198, 1136

MS *m/z*, 255.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

2,3-Dimethyl-1-(pentoxycarbonylmethyl)imidazolium NTf_2 (189d)



Yellow liquid

The title compound was prepared from 2,3- dimethyl-1- (pentoxy carbonyl methyl) imidazolium bromide **189a** (3.36 g, 11.0 mmol) and $LiNTf_2$ (4.59 g, 16.0 mmol) according to the general procedure in 95 % yield (5.30 g, 10.5 mmol).

Molecular formula $C_{14}H_{21}F_6N_3O_6S_2$

Molecular weight 505 g/mol

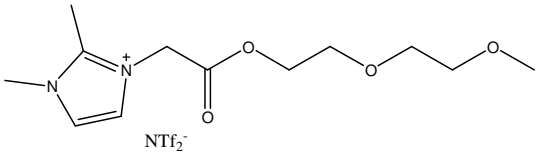
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.28 (d, *J* = 2.2 Hz, 1H), 7.26 (d, *J* = 2.2 Hz, 1H), 4.93 (s, 2H), 4.21 (t, *J* = 6.8 Hz, 2H), 3.82 (s, 3H), 2.56 (s, 3H), 1.68-1.60 (m, 2H), 1.34-1.27 (m, 4H), 0.92 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.78, 145.45, 122.38, 122.37, 119.7 (q, J = 321 Hz, 2*C*F_3's), 67.21, 49.17, 35.48, 27.93, 27.75, 22.18, 13.85, 9.75

IR (thin film on salt plate) (cm^{-1}) 3154, 2962, 2930, 2862, 1751, 1595, 1558, 1546, 1539, 1495, 1452, 1354, 1197, 1137

MS *m/z*, 225.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

2,3-Dimethyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium NTf_2 (191d)



Brown slightly viscous oil

The title compound was prepared from 2,3-dimethyl-1-(methoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **191d** (2.70 g, 8.00 mmol) and $LiNTf_2$ (2.44 g, 8.50 mmol) according to the general procedure in 96 % yield (4.12 g, 7.67 mmol).

Molecular formula $C_{14}H_{21}F_6N_3O_8S_2$

Molecular weight 537 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.29 (d, *J* = 2.2 Hz, 1H), 7.26 (d, *J* = 2.2 Hz, 1H), 4.96 (s, 2H), 4.39 (t, *J* = 4.8 Hz, 2H), 3.82 (s, 3H), 3.74 (t, *J* = 4.8 Hz, 2H), 3.65-3.63 (m, 2H), 3.56-3.54 (m, 2H), 3.37 (s, 3H), 2.56 (s, 3H)

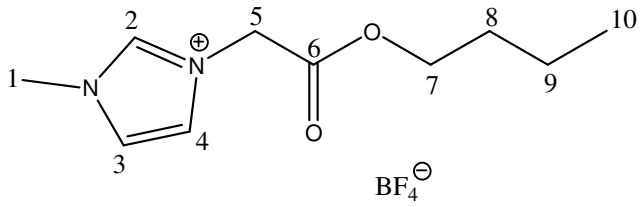
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.76, 145.61, 122.42, 122.35, 119.70 (q, *J* = 319 Hz, 2*C*F_3's), 71.72, 70.39, 68.38, 65.71, 58.97, 49.20, 35.53, 9.79

IR (thin film on salt plate) (cm^{-1}) 3150, 2962, 2857, 1751, 1558, 1539, 1495, 1452, 1354, 1198, 1136

MS *m/z*, 257.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

Achiral BF_4 salts

Representative method for the preparation of BF_4 salts (3-methyl-1-(butoxycarbonylmethyl)imidazolium BF_4) (177b)



To a flask charged with 3-methyl-1-(butoxy carbonyl methyl) imidazolium bromide **177a** (2.94 g, 10.60 mmol) in acetone (10 mL), was added $NaBF_4$ (1.40, 12.7 mmol). The reaction was stirred under reflux for 4 days. The fine white precipitate was filtered and washed with acetone (3 x 5 mL). The filtrate and washings were combined and dried *via* rotary evaporation. The product was then dried under high vacuum for 8 h to give a yellow viscous liquid in 97 % yield (2.92 g, 10.28 mmol).

Molecular formula $C_{10}H_{17}BF_4N_2O_2$

Molecular weight 284 g/mol

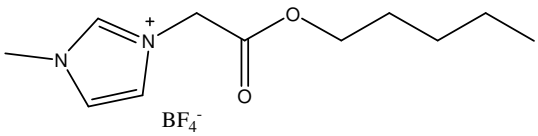
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.94 (s, 1H, *H2*), 7.66 (t, *J* = 1.6 Hz, 1H, *H4*), 7.63 (t, *J* = 1.6 Hz, 1H, *H3*), 5.23 (s, 2H, *H5*), 4.10 (t, *J* = 6.6 Hz, 2H, *H7*), 3.98 (s, 3H, *H1*), 1.54 (tt, *J* = 6.6, 7.2 Hz, 2H, *H8*), 1.30 (tq, *J* = 7.2, 7.4 Hz, 2H, *H9*), 0.80 (t, *J* = 7.4 Hz, 3H, *H10*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.50 (COO), 138.91 (N*C*HN), 124.93 (N*C*H_2), 124.50 (N*C*H_2), 66.64 (O*C*H_2), 50.63 (N*C*H_2), 36.84 (*C*H_2), 31.20 (*C*H_2), 19.60 (*C*H_2), 13.92 (*C*H_3)

IR (thin film on salt plate) (cm^{-1}) 3167, 3126, 2964, 2932, 2972, 1750, 1582, 1569, 1558, 1495, 1455, 1398, 1217, 1181

MS *m/z*, 197.1 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(pentoxycarbonylmethyl)imidazolium BF_4 (178b)



Viscous yellow liquid

The title compound was prepared from 3-methyl-1-(pentoxy carbonyl methyl) imidazolium bromide **178a** (3.11 g, 10.1 mmol) and $NaBF_4$ (1.33 g, 12.1 mmol) according to the general procedure in 95 % yield (2.86 g, 9.60 mmol).

Molecular formula $C_{11}H_{19}BF_4N_2O_2$

Molecular weight 298 g/mol

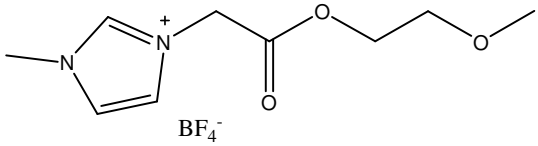
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.08 (s, 1H), 7.45 (t, *J* = 1.8 Hz, 1H), 7.39 (s, *J* = 1.8 Hz, 1H), 5.14 (s, 2H), 4.22 (t, *J* = 6.8 Hz, 2H), 3.97 (s, 3H), 1.72 (tt, *J* = 6.8, 7.1 Hz, 2H), 1.38-1.27 (m, 4H), 0.93 (t, *J* = 7.1 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.24, 137.73, 123.73, 123.27, 66.99, 49.86, 36.37, 27.97, 27.76, 22.22, 13.98

IR (thin film on salt plate) (cm^{-1}) 3167, 3124, 2961, 2931, 2860, 1750, 1582, 1569, 1559, 1495, 1455, 1398, 1230, 1178

MS *m/z*, 211.2 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(methoxyethoxycarbonylmethyl)imidazolium BF_4 (179b)



Brown viscous liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy carbonyl methyl) imidazolium bromide **179a** (2.93 g, 10.5 mmol) and $NaBF_4$ (1.39 g, 12.6 mmol) according to the general procedure in 95 % yield (2.86 g, 10.0 mmol).

Molecular formula $C_9H_{15}BF_4N_2O_3$

Molecular weight 286 g/mol

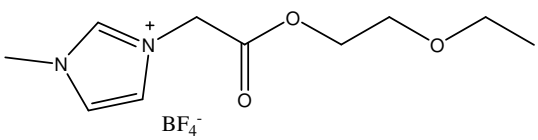
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.71 (s, 1H), 7.43 (s, 2H), 5.11 (s, 2H), 4.33 (t, *J* = 4.4 Hz, 2H), 3.85 (s, 3H), 3.66 (t, *J* = 4.4 Hz, 2H), 3.31 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 170.52, 139.95, 126.08, 125.99, 67.81, 60.59, 52.22, 38.42, 32.74

IR (thin film on salt plate) (cm^{-1}) 3167, 3123, 2961, 2927, 1751, 1583, 1569, 1558, 1495, 1452, 1382, 1226, 1181

MS *m/z*, 199.1 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(ethoxyethoxycarbonylmethyl)imidazolium BF_4 (180b)



Dark orange liquid

The title compound was prepared from 3-methyl-1-(ethoxy ethoxy carbonyl methyl) imidazolium bromide **180a** (2.93 g, 10.0 mmol) and $NaBF_4$ (1.32 g, 12.0 mmol) according to the general procedure in 96 % yield (2.87 g, 9.57 mmol).

Molecular formula $C_{10}H_{17}BF_4N_2O_3$

Molecular weight 300 g/mol

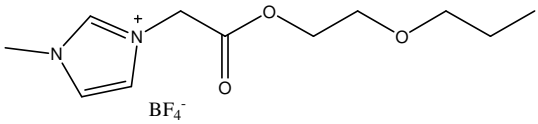
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.69 (s, 1H), 7.35 (t, *J* = 1.8 Hz, 1H), 7.32 (t, *J* = 1.8 Hz, 1H), 4.99 (s, 2H), 4.27 (t, *J* = 4.6 Hz, 2H), 3.84 (s, 3H), 3.60 (t, *J* = 4.6 Hz, 2H), 3.48 (q, *J* = 6.9 Hz, 2H), 1.13 (t, *J* = 6.9 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.36, 137.70, 123.75, 123.33, 67.72, 66.59, 65.76, 49.76, 36.37,15.07

IR (thin film on salt plate) (cm^{-1}) 3167, 3119, 2977, 2937, 2865, 1751, 1582, 1569, 1558, 1495, 1451, 1227, 1217, 1180

MS *m/z*, 213.1 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(propoxyethoxycarbonylmethyl)imidazolium BF_4 (181b)



Dark yellow viscous liquid

The title compound was prepared from 3-methyl-1-(propoxy ethoxy carbonyl methyl) imidazolium bromide **181a** (2.93 g, 9.56 mmol) and $NaBF_4$ (1.26g, 11.5 mmol) according to the general procedure in 97 % yield (2.92 g, 9.30 mmol)

Molecular formula $C_{11}H_{19}BF_4N_2O_3$

Molecular weight 314 g/mol

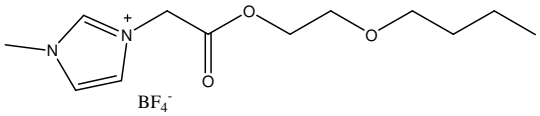
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.94 (s, 1H), 7.66 (t, *J* = 1.8 Hz, 1H), 7.64 (t, *J* = 1.8 Hz, 1H), 5.24 (s, 2H), 4.21 (t, *J* = 4.7 Hz, 2H), 3.98 (s, 3H), 3.53 (t, *J* = 4.7 Hz, 2H), 3.28 (t, *J* = 6.5 Hz, 2H), 1.46 (tq, *J* = 6.5, 7.5 Hz, 2H), 0.77 (t, *J* = 7.5 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.52, 138.92, 123.93, 124.52, 73.23, 68.74, 66.27, 50.62, 36.86, 23.54, 10.83

IR (thin film on salt plate) (cm^{-1}) 3167, 3124, 2966, 2930, 2876, 1751, 1581, 1569, 1558, 1495, 1452, 1394, 1224, 1181

MS *m/z*, 227.2 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(butoxyethoxycarbonylmethyl)imidazolium BF_4 (182b)



Pale yellow viscous liquid

The title compound was prepared from 3-methyl-1-(butoxy ethoxy carbonyl methyl) imidazolium bromide **182a** (2.94 g, 9.15 mmol) and $NaBF_4$ (1.21g, 11.0 mmol) according to the general procedure in 96 % yield (2.88 g, 8.78 mmol).

Molecular formula $C_{12}H_{21}BF_4N_2O_3$

Molecular weight 328 g/mol

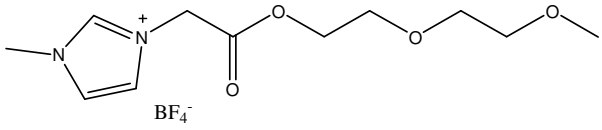
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.83 (s, 1H), 7.42 (t, *J* = 1.8 Hz, 1H), 7.39 (t, *J* = 1.8 Hz, 1H), 5.08 (s, 2H), 4.36 (t, *J* = 4.7 Hz, 2H), 3.94 (s, 3H), 3.68 (t, *J* = 4.7 Hz, 2H), 3.49 (t, *J* = 6.8 Hz, 2H), 1.59 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.41 (tq, *J* = 7.2, 7.4 Hz, 2H), 0.94 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.28, 137.78, 123.70, 123.29, 71.15, 67.94, 65.74, 49.81, 36.41, 31.58, 19.20, 13.90

IR (thin film on salt plate) (cm^{-1}) 3167, 3126, 2961 , 2935, 1750, 1582, 1569, 1558, 1495, 1456, 1451, 1218, 1181

MS *m/z*, 241.2 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium BF_4 (183b)



Orange liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxycarbonylmethyl) imidazolium bromide **183a** (2.95g, 9.12 mmol) and $NaBF_4$ (1.20 g, 10.9 mmol) according to the general procedure in 94 % yield (2.84g, 8.61 mmol).

Molecular formula $C_{11}H_{19}BF_4N_2O_4$

Molecular weight 330 g/mol

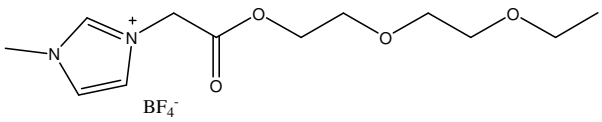
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.71 (s, 1H), 7.38 (d, *J* = 1.6 Hz, 1H) 7.34 (d, *J* = 1.6 Hz, 1H), 4.99 (s, 2H), 4.77 (t, *J* = 4.6 Hz, 2H), 3.86 (s, 3H), 3.66 (t, *J* = 4.6 Hz, 2H), 3.57 (t, *J* = 4.4 Hz, 2H), 3.48 (t, *J* = 4.4 Hz, 2H), 3.28 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.46, 137.67, 123.82, 123.36, 71.69, 70.26, 68.49, 65.50, 58.81, 49.69, 36.31

IR (thin film on salt plate) (cm^{-1}) 3166, 3123, 1750, 1581, 1575, 1569, 1558, 1495, 1451, 1221, 1181

MS *m/z*, 243.2 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(ethoxyethoxyethoxycarbonylmethyl)imidazolium BF_4 (184b)



Orange viscous liquid

The title compound was prepared from 3-methyl-1-(ethoxy ethoxy ethoxy carbonylmethyl)imidazolium bromide **184a** (2.94 g, 8.73 mmol) and $NaBF_4$ (1.15g, 10.48 mmol) according to the general procedure in 96 % yield (2.89 g, 8.40 mmol).

Molecular formula $C_{12}H_{21}BF_4N_2O_4$

Molecular weight 344 g/mol

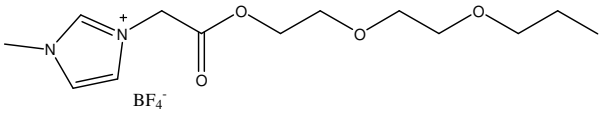
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.94 (s, 1H), 7.66 (t, *J* = 1.8 Hz, 1H) 7.63 (t, *J* = 1.8 Hz, 1H), 5.23 (s, 2H), 4.21 (t, *J* = 4.7 Hz, 2H), 3.98 (s, 3H), 3.59 (t, *J* = 4.7 Hz, 2H), 3.48-3.45 (m, 2H), 3.41-3.39 (m, 2H), 3.36 (q, *J* = 7.0 Hz, 2H), 1.02 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.54, 138.92, 124.94, 124.51, 71.22, 70.56, 69.22, 66.83, 66.27, 50.63, 46.85, 15.59

IR (thin film on salt plate) (cm^{-1}) 3167, 3121, 2970, 2926, 2862, 1756, 1582, 1569, 1558, 1495, 1451, 1218, 1181

MS *m/z*, 257.2 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(propoxyethoxyethoxycarbonylmethyl)imidazolium BF_4 (185b)



Orange liquid

The title compound was prepared from 3-methyl-1-(propoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **185a** (2.94 g, 8.38 mmol) and $NaBF_4$ (1.11g, 10.1 mmol) according to the general procedure in 93 % yield (2.79 g, 7.79 mmol).

Molecular formula $C_{13}H_{23}BF_4N_2O_4$

Molecular weight 358 g/mol

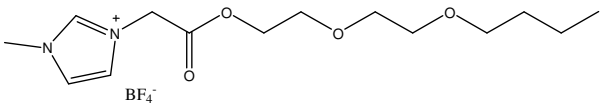
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.95 (s, 1H), 7.45 (t, *J* = 1.8 Hz, 1H), 7.37 (t, *J* = 1.8 Hz, 1H), 5.12 (s, 2H), 4.38 (t, *J* = 4.7 Hz, 2H), 3.97 (s, 3H), 3.75 (t, *J* = 4.7 Hz, 2H), 3.67 (t, *J* = 3.2 Hz, 2H), 3.60 (t, *J* = 3.2 Hz, 2H), 3.44 (t, *J* = 6.8 Hz, 2H), 1.64 (tq, *J* = 6.8, 7.6 Hz, 2H), 0.94 (t, *J* = 7.6 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.23, 137.96, 123.79, 123.13, 73.06, 70.54, 69.89, 68.54, 65.66, 49.85, 36.52, 22.75, 10.49

IR (thin film on salt plate) (cm^{-1}) 3166, 3121, 2964, 2927, 2866, 1750, 1581, 1574, 1569, 1558, 1495, 1452, 1220, 1181

MS *m/z*, 271.3 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(butoxyethoxyethoxycarbonylmethyl)imidazolium BF_4 (186b)



Yellow viscous liquid

The title compound was prepared from 3-methyl-1-(butoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **186a** (2.94 g, 8.06 mmol) and $NaBF_4$ (1.06 g, 9.68 mmol) according to the general procedure in 92 % yield (2.79 g, 7.50 mmol).

Molecular formula $C_{14}H_{25}BF_4N_2O_4$

Molecular weight 372 g/mol

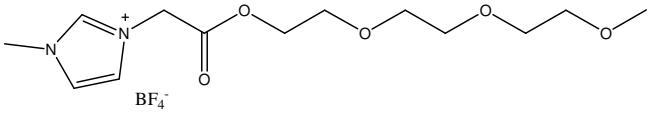
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.09 (s, 1H), 7.80 (t, *J* = 1.8 Hz, 1H), 7.77 (t, *J* = 1.8 Hz, 1H), 5.38 (s, 2H), 4.35 (t, *J* = 4.7 Hz, 2H), 4.11 (s, 3H), 3.74 (t, *J* = 4.7 Hz, 2H), 3.62-3.59 (m, 2H), 3.56-3.53 (m, 2H), 3.46 (t, *J* = 6.4 Hz, 2H), 1.54 (tt, *J* = 6.4, 6.8 Hz, 2H), 1.39 (tq, *J* = 6.8, 7.2 Hz, 2H), 0.92 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.39, 166.33, 137.74, 123.78, 123.30, 72.48, 71.05, 70.18, 68.53, 61.86, 49.74, 30.96, 19.23, 13.92

IR (thin film on salt plate) (cm^{-1}) 3167, 3120, 2956, 2930, 2863, 1751, 1581, 1569, 1558, 1495, 1455, 1217, 1181

MS *m/z*, 285.3 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

3-Methyl-1-(methoxyethoxyethoxyethoxycarbonylmethyl)imidazolium BF_4 (187b)



Brown viscous liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy ethoxy carbonyl methyl) imidazolium bromide **187a** (1.47 g, 4.00 mmol) and $NaBF_4$ (0.55 g, 5.00 mmol) according to the general procedure in 94 % yield (1.41 g, 3.77 mmol).

Molecular formula $C_{13}H_{23}BF_4N_2O_5$

Molecular weight 374 g/mol

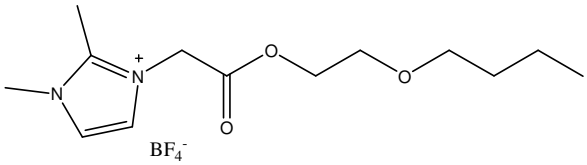
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.79 (s, 1H), 7.47 (s, 1H), 7.40 (s, 1H), 5.08 (s, 2H), 4.34 (t, *J* = 4.6 Hz, 2H), 3.92 (s, 3H), 3.73 (t, *J* = 4.6 Hz, 2H), 3.63-3.58 (m, 6H), 3.55-3.45 (m, 2H), 3.39 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.49, 137.71, 123.83, 123.36, 71.74, 70.32, 70.28, 70.22, 68.49, 65.41, 58.79, 49.69, 36.29

IR (thin film on salt plate) (cm^{-1}) 3165, 3122, 2925, 1751, 1582, 1569, 1558, 1495, 1452, 1217, 1181

MS *m/z*, 287.1 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 86.9 $[BF_4^-]$

2,3-Dimethyl-1-(butoxyethoxycarbonylmethyl)imidazolium BF_4 (190b)



Orange viscous liquid

The title compound was prepared from 2,3-dimethyl-1-(butoxy carbonyl methyl) imidazolium bromide **190a** (2.94 g, 8.78 mmol) and $NaBF_4$ (1.16g, 10.5 mmol) according to the general procedure in 95 % yield (2.85 g, 8.33 mmol).

Molecular formula $C_{13}H_{23}BF_4N_2O_3$

Molecular weight 342 g/mol

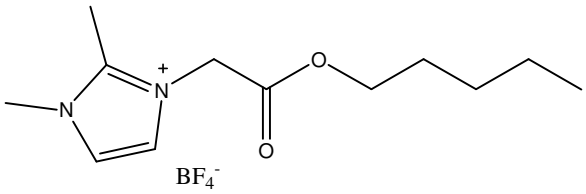
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.32 (d, *J* = 2.0 Hz, 1H), 7.31 (d, *J* = 2.0 Hz, 1H), 4.98 (s, 2H), 4.36 (t, *J* = 4.8 Hz, 2H), 3.80 (s, 3H), 3.68 (t, *J* = 4.8 Hz, 2H), 3.49 (t, *J* = 6.8 Hz, 2H), 2.53 (s, 3H), 1.59 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.41 (tq, *J* = 7.2, 7.4 Hz, 2H), 0.95 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.26, 145.68, 122.41, 122.35, 71.13, 67.96, 65.61, 48.90, 35.26, 31.59, 19.20, 13.90, 9.49

IR (thin film on salt plate) (cm^{-1}) 3157, 2962, 2933, 1750, 1595, 1558, 1544, 1495, 1451, 1391, 1248, 1217

MS *m/z*, 255.2 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

2,3-Dimethyl-1-(pentoxycarbonylmethyl)imidazolium BF_4 (189b)



Yellow viscous liquid

The title compound was prepared from 2,3-dimethyl-1-(pentoxy carbonyl methyl) imidazolium bromide **189a** (2.93 g, 9.62 mmol) and $NaBF_4$ (1.28 g, 11.6 mmol) according to the general procedure in 93 % yield (2.79 g, 8.94 mmol)

Molecular formula $C_{12}H_{21}BF_4N_2O_2$

Molecular weight 312 g/mol

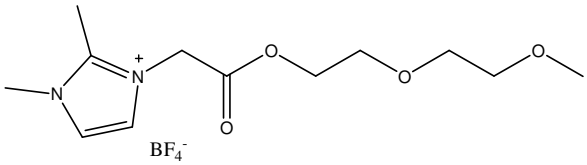
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.21 (s, 2H), 4.89 (s, 2H), 4.15 (t, *J* = 6.8 Hz, 2H), 3.61 (s, 3H), 2.98 (s, 3H), 1.65-1.60 (m, 2H), 1.30-1.28 (m, 4H), 0.86 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.24, 145.70, 122.39, 122.29, 67.06, 49.10, 35.38, 28.02, 27.80, 22.22, 13.91, 9.73

IR (thin film on salt plate) (cm^{-1}) 3440, 3148, 2958, 2930, 2860, 1748, 1546, 1454, 1399, 1225, 1049, 1035

MS *m/z*, 225.2 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

2,3-Dimethyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium BF_4 (191b)



Orange viscous liquid

The title compound was prepared from 2,3-dimethyl-1-(methoxy ethoxy carbonylmethyl)imidazolium bromide **191a** (2.94 g, 8.73 mmol) and $NaBF_4$ (1.16g, 10.5 mmol) according to the general procedure in 94 % yield (2.82 g, 8.20 mmol).

Molecular formula $C_{12}H_{21}BF_4N_2O_4$

Molecular weight 344 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.64 (s, 2H), 5.30 (s, 2H), 4.36 (t, *J* = 4.7 Hz, 2H), 3.99 (s, 3H), 3.73 (t, *J* = 4.7 Hz, 2H), 3.62 (t, *J* = 4.6 Hz, 2H), 3.51 (t, *J* = 4.6 Hz, 2H), 3.31 (s, 3H), 2,73 (s, 3H)

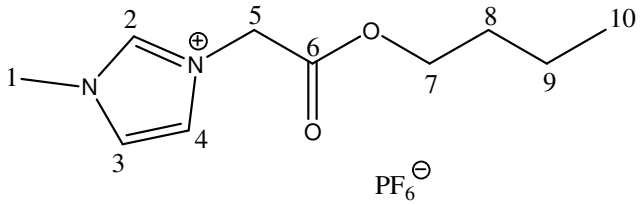
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 171.66, 151.56, 127.67, 127.57, 76.85, 75.22, 72.50, 70.48, 63.13, 53.96, 40.65, 14.68

IR (thin film on salt plate) (cm^{-1}) 3154, 2926, 2862, 1750, 1558, 1546, 1539, 1495, 1451, 1247, 1217

MS *m/z*, 257.2 $[M\text{-}BF_4^-]^+$; MS: *m/z*, 87.0 $[BF_4^-]$

Achiral PF_6 salts

Representative method for the preparation of PF_6 salts (3-methyl-1-(butoxycarbonylmethyl)imidazolium PF_6) (177c)



To a flask charged with 3-methyl-1-(butoxy carbonyl methyl) imidazolium bromide **177a** (2.02 g, 7.31 mmol) in acetone (10 mL), was added KPF_6 (1.61 g, 8.77 mmol). The reaction was stirred under reflux for 4 days. The fine white precipitate was filtered and washed with acetone (3 x 5 mL). The filtrate and washings were combined and dried *via* rotary evaporation. The product was then dried under high vacuum for 8 h to give a brown viscous liquid in 93 % yield (2.33 g, 6.81 mmol).

Molecular formula $C_{10}H_{17}PF_6N_2O_2$

Molecular weight 342 g/mol

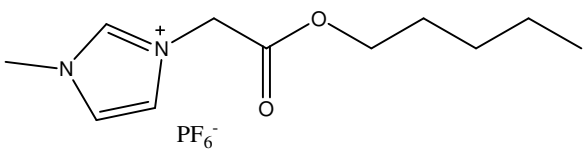
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.06 (s, 1H, *H2*), 7.79 (t, *J* = 1.8 Hz, 1H, *H4*), 7.77 (t, *J* = 1.8 Hz, 1H, *H3*), 5.37 (s, 2H, *H5*), 4.24 (t, *J* = 6.5 Hz, 2H, *H7*), 4.14 (s, 3H, *H1*), 1.67 (tt, *J* = 6.5, 6.8 Hz, 2H, *H8*), 1.42 (tq, *J* = 6.8, 7.3 Hz, 2H, *H9*), 0.94 (t, *J* = 7.3 Hz, 3H, *H10*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.41 (*C*OO), 138.73 (N*C*HN), 124.97 (N*C*H_2), 124.56 (N*C*H_2), 67.01 (O*C*H_2), 50.70 (N*C*H_2), 36.90 (*C*H_2), 28.86 (*C*H_2), 28.58 (*C*H_2), 14.22 (*C*H_3)

IR (thin film on salt plate) (cm^{-1}) 3178, 3127, 2966, 2871, 1751, 1582, 1569, 1559, 1495, 1452, 1398, 1218, 1181

MS *m/z*, 197.1 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(pentoxycarbonylmethyl)imidazolium PF_6 (178c)



Brown viscous liquid

The title compound was prepared from 3-methyl-1-(pentoxy carbonyl methyl) imidazolium bromide **178a** (2.44 g, 8.40 mmol) and KPF_6 (1.86 g, 10.1 mmol) according to the general procedure in 98 % yield (2.94 g, 8.26 mmol).

Molecular formula $C_{11}H_{19}PF_6N_2O_2$

Molecular weight 356 g/mol

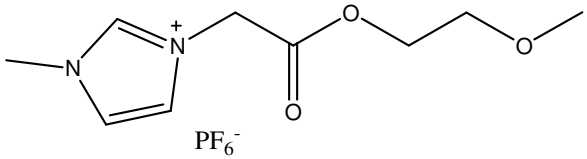
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.01 (s, 1H), 7.80 (t, *J* = 1.8 Hz, 1H), 7.77 (t, *J* = 1.8 Hz, 1H), 5.40 (s, 2H), 4.32 (t, *J* = 4.8 Hz, 2H), 4.12 (s, 3H), 1.73-1.64 (m, 2H), 1.40-1.31 (m, 4H), 0.95 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.41, 138.73, 124.97, 124.56, 67.01, 50.70, 30.08, 29.51, 29.31, 28.86, 14.22

IR (thin film on salt plate) (cm^{-1}) 3179, 3133, 2962, 2933, 2864, 1751, 1582, 1569, 1559, 1495, 1456, 1398, 1232, 1181

MS *m/z*, 211.2 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(methoxyethoxycarbonylmethyl)imidazolium PF_6 (179c)



Brown solid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy carbonylmethyl)imidazolium bromide **179a** (2.43 g, 8.72 mmol) and KPF_6 (1.93 g, 10.5 mmol) according to the general procedure in 96 % yield (2.88 g, 8.37 mmol).

Molecular formula $C_9H_{15}PF_6N_2O_3$

Molecular weight 344 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.89 (s, 1H), 7.64 (t, *J* = 1.8 Hz, 1H), 7.61 (t, *J* = 1.8 Hz, 1H), 5.23 (s, 2H), 4.21 (t, *J* = 4.6 Hz, 2H), 3.99 (s, 3H), 3.48 (t, *J* = 4.6 Hz, 2H), 3.18 (s, 3H)

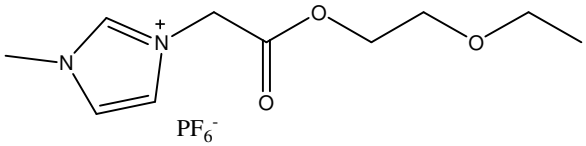
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.47, 138.74, 124.96, 124.56, 70.55, 66.08, 58.78,50.64, 36.89

MP (°C) 58 – 60

IR (KBr disc) (cm^{-1}) 3174, 1752, 1581, 1453, 1255, 1182, 1096, 1041

MS *m/z*, 199.1 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(ethoxyethoxycarbonylmethyl)imidazolium PF_6 (180c)



Yellow viscous liquid

The title compound was prepared from 3-methyl-1-(ethoxy ethoxy carbonylmethyl)imidazolium bromide **180a** (2.46 g, 8.38 mmol) and KPF_6 (1.86 g, 10.1 mmol) according to the general procedure in 98 % yield (2.94 g, 8.21 mmol).

Molecular formula $C_{10}H_{17}PF_6N_2O_3$

Molecular weight 358 g/mol

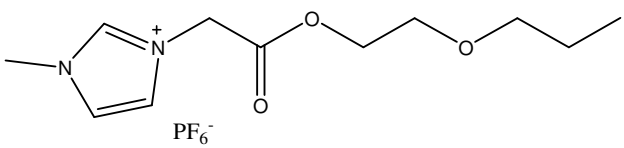
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.91 (s, 1H), 7.66 (t, *J* = 1.8 Hz, 1H), 7.63 (t, *J* = 1.8 Hz, 1H), 5.24 (s, 2H), 4.20 (t, *J* = 4.7 Hz, 2H), 4.00 (s, 3H), 3.53 (t, *J* = 4.7 Hz, 2H), 3.38 (q, *J* = 7.1 Hz, 2H), 1.02 (t, *J* = 7.1 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.49, 138.76, 124.98, 124.58, 68.51, 66.56, 66.36, 50.67, 36.91, 15.48

IR (thin film on salt plate) (cm^{-1}) 3179, 3131, 2972, 2927, 2865, 1751, 1579, 1569, 1559, 1495, 1451, 1398, 1225, 1180, 1117

MS *m/z*, 213.1 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(propoxyethoxycarbonylmethyl)imidazolium PF_6 (181c)



Yellow viscous liquid

The title compound was prepared from 3-methyl-1-(propoxy ethoxy carbonyl methyl) imidazolium bromide **181a** (2.47 g, 8.06 mmol) and KPF_6 (1.78 g, 9.68 mmol) according to the general procedure in 97 % yield (2.91 g, 7.82 mmol).

Molecular formula $C_{11}H_{19}PF_6N_2O_3$

Molecular weight 372 g/mol

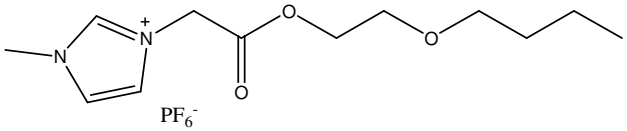
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.08 (s, 1H), 7.81 (t, *J* = 1.8 Hz, 1H), 7.76 (t, *J* = 1.8 Hz, 1H), 5.44 (s, 2H), 4.35 (t, *J* = 4.8 Hz, 2H), 4.13 (s, 3H), 3.63 (t, *J* = 4.8 Hz, 2H), 3.41 (t, *J* = 4.8 Hz, 2H), 1.60 (tq, *J* = 4.8, 7.0 Hz, 2H), 0.90 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.45, 138.75, 124.10, 124.58, 73.23, 68.72, 66.33, 50.68, 36.92, 23.53, 10.82

IR (thin film on salt plate) (cm^{-1}) 3179, 3125, 2970, 2931, 2877, 1751, 1582, 1569, 1559, 1495, 1451, 1398, 1218, 1181, 1113

MS *m/z*, 227.2 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(butoxyethoxycarbonylmethyl)imidazolium PF_6 (182c)



Yellow viscous liquid

The title compound was prepared from 3-methyl-1-(butoxy ethoxy carbonyl methyl) imidazolium bromide **182a** (2.49 g, 7.77 mmol) and KPF_6 (1.70 g, 9.24 mmol) according to the general procedure in 95 % yield (2.85 g, 7.38 mmol).

Molecular formula $C_{12}H_{21}PF_6N_2O_3$

Molecular weight 386 g/mol

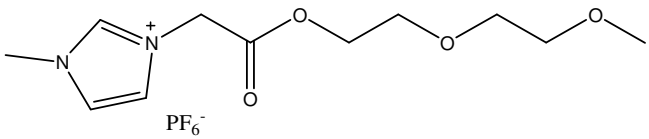
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.46 (s, 1H), 7.34 (t, *J* = 1.8 Hz, 1H), 7.32 (t, *J* = 1.8 Hz, 1H), 4.96 (s, 2H), 4.35 (t, *J* = 4.6 Hz, 2H), 3.88 (s, 3H), 3.67 (t, *J* = 4.8 Hz, 2H), 3.49 (t, *J* = 6.8 Hz, 2H), 1.58 (tt, *J* = 6.8, 7.2 H, 2H), 1.40 (tq, *J* = 7.2, 7.5 Hz, 2H), 0.94 (t, *J* = 7.5 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.05, 137.24, 123.63, 123.37, 71.09, 67.87, 65.78, 49.67, 36.26, 31.55, 19.16, 13.86

IR (thin film on salt plate) (cm^{-1}) 3178, 3127, 2961, 2934, 2870, 1751, 1582, 1569, 1559, 1495, 1451, 1393, 1217, 1180

MS *m/z*, 241.2 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium PF_6 (183c)



Orange viscous liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy carbonyl methyl) imidazolium bromide **183a** (3.55 g, 11.0 mmol) and KPF_6 (3.31 g, 18.0 mmol) according to the general procedure in 91 % yield (3.87 g, 9.97 mmol).

Molecular formula $C_{11}H_{19}PF_6N_2O_4$

Molecular weight 388 g/mol

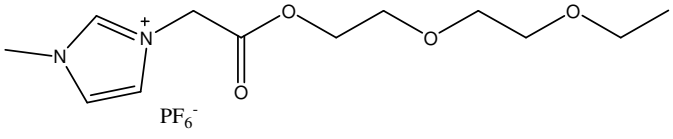
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.60 (s, 1H), 7.53 (tt, *J* = 1.8, 1.8 Hz, 2H), 5.59 (s, 2H), 4.45 (t, *J* = 4.6 Hz, 2H), 4.00 (s, 3H), 3.82 (t, *J* = 4.6 Hz, 2H), 3.72 (t, *J* = 4.6 Hz, 2H), 3.62 (t, *J* = 4.6 Hz, 2H), 3.44 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.98, 136.76, 123.33, 123.17, 71.16, 69.69, 67.85, 65.23, 57.54, 49.44, 35.84

IR (thin film on salt plate) (cm^{-1}) 3172, 3124, 2926, 1751, 1580, 1569, 1559, 1495, 1457, 1218, 1181, 1106

MS *m/z*, 243.2 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(ethoxyethoxyethoxycarbonylmethyl)imidazolium PF_6 (184c)



Orange viscous liquid

The title compound was prepared from 3-methyl-1-(ethoxyethoxyethoxycarbonylm ethyl) imidazolium bromide **184a** (2.51 g, 7.46 mmol) and KPF_6 (1.65 g, 8.95 mmol) according to the general procedure in 96 % yield (2.88 g, 7.16 mmol).

Molecular formula $C_{12}H_{21}PF_6N_2O_4$

Molecular weight 402 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.65 (s, 1H), 7.39 (t, *J* = 1.6 Hz, 1H), 7.31 (t, *J* = 1.6 Hz, 1H), 5.02 (s, 2H), 4.41 (t, *J* = 4.6 Hz, 2H), 3.96 (s, 3H), 3.78 (t, *J* = 4.6 Hz,

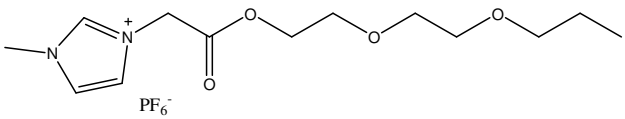
2H), 3.68-3.66 (m, 2H), 3.62-3.60 (m, 2H), 3.57 (q, *J* = 7.0 Hz, 2H), 1.23 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.30, 137.56, 123.81, 123.40, 70.06, 69.34, 68.03, 65.68, 65.18, 49.51, 35.74, 14.44

IR (thin film on salt plate) (cm^{-1}) 3175, 3123, 2966, 2926, 2869, 1751, 1582, 1569, 1559, 1495, 1451, 1215, 1180, 1105

MS *m/z*, 257.1 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(propoxyethoxyethoxycarbonylmethyl)imidazolium PF_6 (185c)



Yellow viscous liquid

The title compound was prepared from 3-methyl-1-(propoxy ethoxy ethoxycarbonylmethyl) imidazolium bromide **185a** (2.53 g, 7.21 mmol) and KPF_6 (1.59 g, 8.65 mmol) according to the general procedure in 91 % yield (2.72 g, 6.54 mmol).

Molecular formula $C_{13}H_{23}PF_6N_2O_4$

Molecular weight 416 g/mol

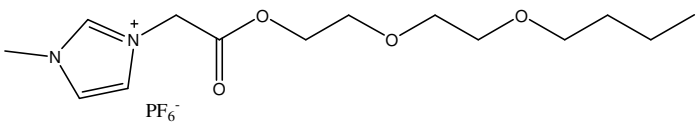
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.51 (s, 1H), 7.29 (s, 1H), 7.22 (s, 1H), 4.91 (s, 2H), 4.31 (t, *J* = 4.6 Hz, 2H), 3.86 (s, 3H), 3.68 (t, *J* = 4.6 Hz, 2H), 3.59 (t, *J* = 4.8 Hz, 2H), 3.53 (t, *J* = 4.8 Hz, 2H), 3.36 (t, *J* = 6.8 Hz, 2H), 1.54 (m, 2H), 0.85 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.01, 137.45, 123.75, 123.29, 73.02, 70.49, 69.85, 68.47, 65.70, 49.76, 36.43, 22.73, 10.47

IR (thin film on salt plate) (cm^{-1}) 3178, 3126, 2962, 2927, 2873, 1751, 1581, 1569, 1559, 1495, 1452, 1400, 1218, 1180

MS *m/z*, 271.3 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(butoxyethoxyethoxycarbonylmethyl)imidazolium PF_6 (186c)



Brown viscous liquid

The title compound was prepared from 3-methyl-1-(butoxyethoxyethoxycarbonyl methyl) imidazolium bromide **186a** (2.96 g, 8.10 mmol) and KPF_6 (2.21 g, 12.0 mmol) according to the general procedure in 79 % yield (2.75 g, 6.40 mmol).

Molecular formula $C_{14}H_{25}PF_6N_2O_4$

Molecular weight 430 g/mol

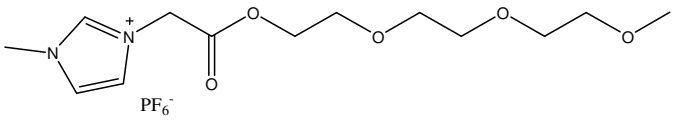
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.47 (s, 1H), 7.29 (s, 1H), 7.23 (s, 1H), 4.90 (s, 2H), 4.30 (t, *J* = 4.6 Hz, 2H), 3.85 (s, 3H), 3.67 (t, *J* = 4.6 Hz, 2H), 3.58-3.56 (m, 2H), 3.52-3.50 (m, 2H), 3.40 (t, *J* = 6.8 Hz, 2H), 1.51 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.28 (tq, *J* = 7.2, 7.5 Hz, 2H), 0.86 (t, *J* = 7.5 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.95, 137.48, 123.75, 123.22, 71.18, 70.52, 69.91, 68.48, 65.73, 49.75, 36.44, 19.24, 13.93

IR (thin film on salt plate) (cm^{-1}) 3179, 3125, 2957, 2933, 2866, 1756, 1580, 1569, 1559, 1495, 1452, 1218, 1181, 1106

MS *m/z*, 285.3 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

3-Methyl-1-(methoxyethoxyethoxyethoxycarbonylmethyl)imidazolium PF_6 (187c)



Brown viscous liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **187a** (1.47 g, 4.00 mmol) and KPF_6 (0.92 g, 5.00 mmol) according to the general procedure in 57 % yield (0.98 g, 2.27 mmol).

Molecular formula $C_{13}H_{23}PF_6N_2O_5$

Molecular weight 432 g/mol

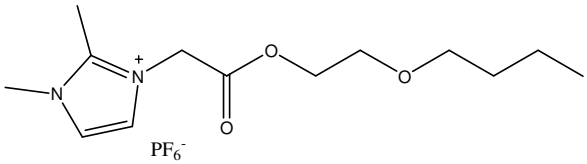
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.54 (s, 1H), 7.40 (t, *J* = 1.8 Hz, 1H), 7.35 (t, *J* = 1.8 Hz, 1H), 5.32 (s, 2H), 4.33 (t, *J* = 4.5 Hz, 2H), 3.89 (s, 3H), 3.72 (t, *J* = 4.5 Hz, 2H), 3.64-3.59 (m, 6H), 3.55 (t, *J* = 4.6 Hz, 2H), 3.33 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.24, 137.38, 123.75, 123.37, 71.69, 70.27, 70.23, 70.17, 68.41, 65.47, 58.69, 49.59, 36.20

IR (thin film on salt plate) (cm^{-1}) 3176, 3121, 2926, 2862, 1751, 1582, 1569, 1559, 1495, 1452, 1402, 1224, 1180

MS *m/z*, 287.3 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

2,3-Dimethyl-1-(butoxyethoxycarbonylmethyl)imidazolium PF_6 (190c)



Brown viscous liquid

The title compound was prepared from 2,3-dimethyl-1-(butoxy ethoxy carbonyl methyl) imidazolium bromide **190a** (2.51 g, 7.50 mmol) and KPF_6 (1.66 g, 9.00 mmol) according to the general procedure in 97 % yield (2.91 g, 7.28 mmol).

Molecular formula $C_{13}H_{23}PF_6N_2O_3$

Molecular weight 400 g/mol

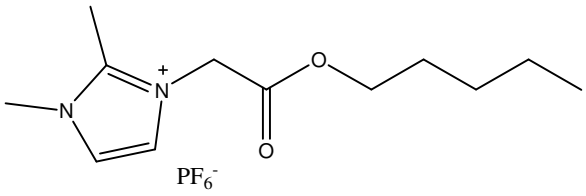
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.25 (d, *J* = 2.4Hz, 1H), 7.22 (d, *J* = 2.4 Hz, 1H), 4.89 (s, 2H), 4.35 (t, *J* = 4.8 Hz, 2H), 3.77 (s, 3H), 3.67-3.65 (m, 2H), 3.49 (t, *J* = 6.6 Hz, 2H), 2.51 (s, 3H), 1.59-1.52 (m, 2H), 1.41-1.32 (m, 2H), 0.94 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.98, 145.59, 122.38, 122.21, 71.09, 67.90, 65.70, 48.80, 35.18, 31.59, 19.19, 13.88, 9.24

IR (thin film on salt plate) (cm^{-1}) 3163, 2962, 2931, 2867, 1751, 1596, 1559, 1539, 1495, 1451, 1392, 1245, 1218, 1123

MS *m/z*, 255.2 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

2,3-Dimethyl-1-(pentoxycarbonylmethyl)imidazolium PF_6 (189c)



Yellow solid

The title compound was prepared from 2,3-dimethyl-1-(pentoxy carbonyl methyl) imidazolium bromide **189a** (2.47 g, 8.11 mmol) and KPF_6 (1.79 g, 9.73 mmol) according to the general procedure in 97 % yield (2.91 g, 7.86 mmol).

Molecular formula $C_{12}H_{21}PF_6N_2O_2$

Molecular weight 370 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.61 (s, 2H), 5.28 (s, 2H), 4.23 (t, *J* = 6.6 Hz, 2H), 4.0 (s, 3H), 3.73 (s, 3H), 1.71-1.64 (m, 2H), 1.37-1.31 (m, 4H), 0.92 (t, *J* = 7.0 Hz, 3H)

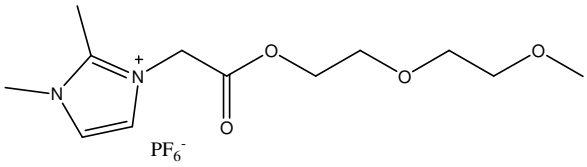
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.27, 147.15, 123.39, 123.26, 67.08, 49.46, 35.76, 28.83, 28.58, 22.91, 74.24, 9.73

MP (°C) 40 – 42

IR (KBr disc) (cm^{-1}) 3165, 2956, 2930, 1752, 1399, 1253, 1231, 1212, 1049

MS *m/z*, 225.2 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

2,3-Dimethyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium PF_6 (191c)



Orange viscous liquid

The title compound was prepared from 2,3-dimethyl-1-(methoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **191a** (2.51 g, 7.46 mmol) and KPF_6 (1.65 g, 8.95 mmol) according to the general procedure in 95 % yield (2.84 g, 7.06 mmol).

Molecular formula $C_{12}H_{21}PF_6N_2O_4$

Molecular weight 402 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.59 (s, 2H), 5.27 (s, 2H), 4.38 (t, *J* = 4.6 Hz, 2H), 3.98 (s, 3H), 3.73 (t, *J* = 4.6 Hz, 2H), 3.63 (t, *J* = 4.6 Hz, 2H), 3.52 (t, *J* = 4.6 Hz, 2H), 3.12 (s, 3H), 2.72 (s, 3H)

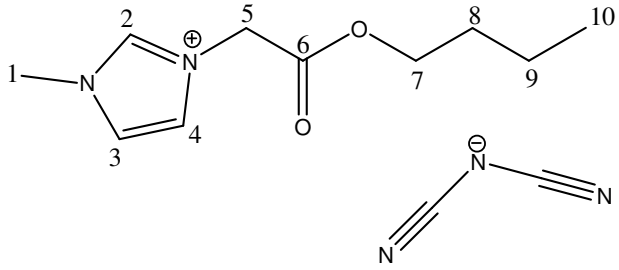
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 167.27, 147.21, 123.38, 123.22, 72.46, 70.88, 69.20, 66.23, 58.81, 49.65, 35.74, 9.70

IR (thin film on salt plate) (cm^{-1}) 3160, 2926, 2861, 1751, 1596, 1559, 1539, 1495, 1452, 1400, 1245, 1217, 1106

MS *m/z*, 257.2 $[M\text{-}PF_6^-]^+$; MS: *m/z*, 145.0 $[PF_6^-]$

Achiral $N(CN)_2$ salts

Representative method for the preparation of $N(CN)_2$ salts (3-methyl-1-(butoxycarbonylmethyl)imidazolium $N(CN)_2$) (177e)



A dry flask was charged with 3-methyl-1-(butoxy carbonyl methyl) imidazolium bromide **177a** (3.05 g, 11.00 mmol) and acetonitrile (10 mL) under a nitrogen atmosphere. $NaN(CN)_2$ (1.42 g, 16.0 mmol) was added in one portion and the suspension was stirred vigorously for 4 days at RT. The fine white precipitate was filtered quickly in air and washed with dry acetonitrile (3 x 5 mL). The filtrate and washings were combined, solvent removed by rotary evaporation and then under high vacuum to give a yellow oil in 87 % yield (2.51 g, 9.54 mmol).

Molecular formula $C_{12}H_{17}N_5O_2$

Molecular weight 263 g/mol

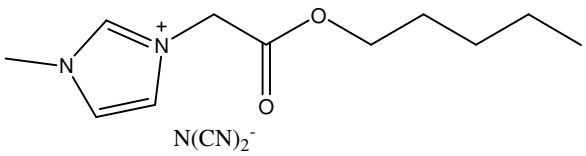
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.82 (s, 1H, *H2*), 7.56 (t, *J* = 1.8 Hz, 1H, *H4*), 7.46 (t, *J* = 1.8 Hz, 1H, *H3*), 5.32 (s, 2H, *H5*), 4.15 (t, *J* = 6.8 Hz, 2H, *H7*), 4.02 (s, 3H, *H1*), 1.61 (tt, *J* = 6.8, 7.2 Hz, 2H, *H8*), 1.33 (tq, *J* = 7.2, 7.5 Hz, 2H, *H9*), 0.87 (t, *J* = 7.5 Hz, 3H, H*10*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 164.10 (*C*OO), 136.12 (N*C*HN), 121.89 (N*C*H_2), 121.18 (N*C*H_2), 64.85 (O*C*H_2), 48.22 (N*C*H_2), 34.87 (*C*H_2), 28.31 (*C*H_2), 16.96 (*C*H_2), 11.67 (*C*H_3) Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2962, 2931, 2861, 2241, 2139, 1750, 1569, 1558, 1539, 1495, 1452, 1217, 1177

MS *m/z*, 197.1 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(pentoxycarbonylmethyl)imidazolium $N(CN)_2$ (178e)



Bright yellow oil

The title compound was prepared from 3-methyl-1-(pentoxy carbonyl methyl) imidazolium bromide **178a** (3.20 g, 11.0 mmol) and $NaN(CN)_2$ (1.34 g, 15.0 mmol) according to the general procedure in 98 % yield (3.00 g, 10.8 mmol).

Molecular formula $C_{13}H_{19}N_5O_2$

Molecular weight 277 g/mol

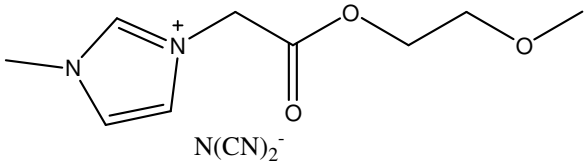
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.66 (s, 1H), 7.63 (t, *J* = 1.8 Hz, 1H), 7.56 (t, *J* = 1.8 Hz, 1H), 5.29 (s, 2H), 4.13 (t, *J* = 6.8 Hz, 2H), 4.02 (s, 3H), 1.62-1.59 (m, 2H), 1.26-1.22 (m, 4H), 0.84 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 164.05, 135.78, 121.97, 121.34, 65.02, 48.12, 34.78, 25.94, 25.74, 20.16, 11.90 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2958, 2933, 2861, 2240, 2138, 1750, 1569, 1558, 1495, 1457, 1229, 1177

MS *m/z*, 211.2 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(methoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (179e)



Brown oil

The title compound was prepared from 3-methyl-1-(methoxy ethoxy carbonyl methyl) imidazolium bromide **179a** (3.35 g, 12.0 mmol) and $NaN(CN)_2$ (1.78 g, 20.0 mmol) according to the general procedure in 80 % yield (2.55 g, 9.62 mmol).

Molecular formula $C_{11}H_{15}N_5O_3$

Molecular weight 265 g/mol

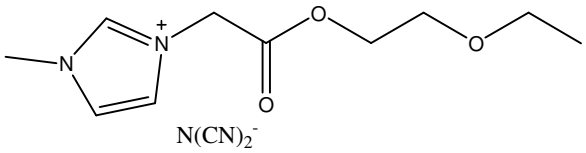
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.81 (s, 1H), 7.66 (t, *J* = 1.8 Hz, 1H), 7.55 (t, *J* = 1.8 Hz, 1H), 5.44 (s, 2H), 4.35 (t, *J* = 4.5 Hz, 2H), 4.06 (s, 3H), 3.63 (t, *J* = 4.5 Hz, 2H), 3.37 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 164.30, 136.09, 121.94, 121.24, 67.86, 63.55, 56.95, 48.22, 34.91 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 3099, 2928, 2857, 1750, 1636, 1574, 1558, 1495, 1452, 1378, 1216, 1176

MS *m/z*, 199.1 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(ethoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (180e)



Brown viscous liquid

The title compound was prepared from 3-methyl-1-(ethoxy ethoxy carbonylmethyl)imidazolium bromide **180a** (2.84 g, 9.70 mmol) and $NaN(CN)_2$ (0.98 g, 11.0 mmol) according to the general procedure in 99 % yield (2.68 g, 9.61 mmol).

Molecular formula $C_{12}H_{17}N_5O_3$

Molecular weight 279 g/mol

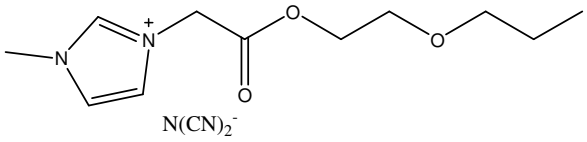
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.95 (s, 1H), 7.60 (t, *J* = 1.6 Hz, 1H), 7.50 (t, *J* = 1.6 Hz, 1H), 5.45 (s, 2H), 4.37 (t, *J* = 4.6 Hz, 2H), 4.09 (s, 2H), 3.68 (t, *J* = 4.6 Hz, 2H), 3.55 (q, *J* = 7.0 Hz, 2H), 1.21 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.20, 138.22, 123.86, 123.14, 67.72, 66.69, 65.85, 50.23, 36.91, 15.12 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2974, 2928, 2862, 2139, 1750, 1633, 1569, 1558, 1495, 1451, 1217, 1177, 1115

MS *m/z*, 213.1 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(propoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (181e)



Pale brown viscous liquid

The title compound was prepared from 3-methyl-1-(propoxy ethoxy carbonylmethyl)imidazolium bromide **181a** (3.38 g, 11.0 mmol) and $NaN(CN)_2$ (1.42 g, 16.0 mmol) according to the general procedure in 91 % yield (2.93 g, 10.0 mmol).

Molecular formula $C_{13}H_{19}N_5O_3$

Molecular weight 293 g/mol

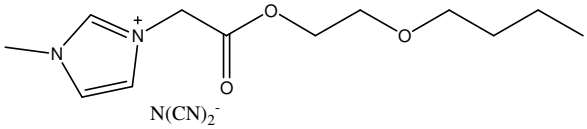
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.82 (s, 1H), 7.61 (t, *J* = 1.8 Hz, 1H), 7.53 (t, *J* = 1.8 Hz, 1H), 5.41 (s, 2H), 4.35 (t, *J* = 4.6 Hz, 2H), 4.07 (s, 3H), 3.66 (t, *J* = 4.6 Hz, 2H), 3.42 (t, *J* = 6.8 Hz, 2H), 1.59 (tq, *J* = 6.8, 7.4 Hz, 2H), 0.90 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.16, 138.13, 123.86, 123.22, 73.02, 67.89, 65.83, 50.22, 36.90, 22.72, 10.49 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2962, 2927, 2861, 2139, 1751, 1636, 1558, 1539, 1495, 1452, 1216, 1175, 1106

MS *m/z*, 227.2 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(butoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (182e)



Dark yellow oil

The title compound was prepared from 3-methyl-1-(butoxy ethoxy carbonylmethyl)imidazolium bromide **182a** (3.85 g, 12.0 mmol) and $NaN(CN)_2$ (1.78 g, 20.0 mmol) according to the general procedure in 51 % yield (1.87 g, 6.09 mmol).

Molecular formula $C_{14}H_{21}N_5O_3$

Molecular weight 307 g/mol

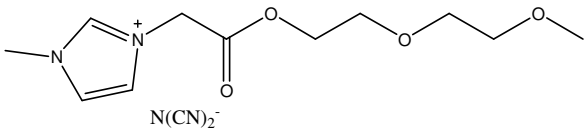
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.87 (s, 1H), 7.58 (t, *J* = 1.8 Hz, 1H), 7.50 (t, *J* = 1.8 Hz, 1H), 5.41 (s, 2H), 4.36 (t, *J* = 4.8 Hz, 2H), 4.08 (s, 3H), 3.67 (t, *J* = 4.8 Hz, 2H), 3.46 (t, *J* = 6.8 Hz, 2H), 1.55 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.35 (tq, *J* = 7.2, 7.5 Hz, 2H), 0.91 (t, *J* = 7.5 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.10, 138.21, 123.83, 123.14, 71.22, 67.92, 65.87, 50.23, 36.91, 31.57, 19.21, 13.94 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2960, 2933, 2865, 2139, 1751, 1633, 1569, 1558, 1495, 1452, 1215, 1177, 1117

MS *m/z*, 241.2 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (183e)



Orange viscous liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **183a** (2.91 g, 9.00 mmol) and $NaN(CN)_2$ (0.89 g, 10.0 mmol) according to the general procedure in 94 % yield (2.59 g, 8.38 mmol).

Molecular formula $C_{14}H_{19}N_5O_4$

Molecular weight 309 g/mol

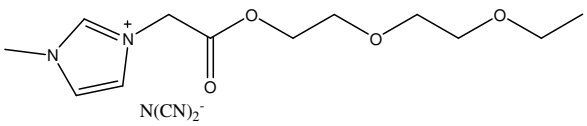
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.95 (s, 1H), 7.49 (t, *J* = 1.6 Hz, 1H), 7.30 (t, *J* = 1.6 Hz, 1H), 5.38 (s, 2H), 4.33 (t, *J* = 4.6 Hz, 2H), 4.01 (s, 3H), 3.68 (t, *J* = 4.6 Hz, 2H), 3.59-3.53 (m, 2H), 3.50-3.44 (m, 2H), 3.31 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.14, 138.63, 123.85, 122.81, 71.97, 70.47, 68.53, 65.70, 59.03, 50.26, 36.90 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2926, 2859, 2139, 1750, 1566, 1558, 1495, 1452, 1217, 1175, 1104

MS *m/z*, 243.2 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(ethoxyethoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (184e)



Brown viscous liquid

The title compound was prepared from 3-methyl-1-(ethoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **184a** (2.53 g, 7.50 mmol) and $NaN(CN)_2$ (0.76 g, 8.50 mmol) according to the general procedure in 99 % yield (2.40 g, 7.43 mmol).

Molecular formula $C_{14}H_{21}N_5O_4$

Molecular weight 323 g/mol

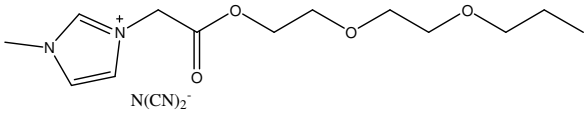
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.01 (s, 1H), 7.61 (t, *J* = 1.8 Hz, 1H), 7.43 (t, *J* = 1.8 Hz, 1H), 5.46 (s, 2H), 4.40 (t, *J* = 4.8 Hz, 2H), 4.09 (s, 3H), 3.76 (t, *J* = 4.8 Hz, 2H), 3.67-3.65 (m, 2H), 3.62-3.59 (m, 2H), 3.55 (q, *J* = 7.0 Hz, 2H), 1.21 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.16, 138.47, 123.92, 122.91, 70.65, 69.70, 68.53, 66.67, 65.71, 50.94, 36.90, 15.18 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2927, 2868, 2139, 1750, 1636, 1569, 1558, 1495, 1451, 1215, 1177, 1105

MS *m/z*, 257.2 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(propoxyethoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (185e)



Yellow viscous liquid

The title compound was prepared from 3-methyl-1-(propoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **185a** (2.70 g, 7.70 mmol) and $NaN(CN)_2$ (0.80 g, 9.00 mmol) according to the general procedure in 85 % yield (2.20 g, 6.53 mmol).

Molecular formula $C_{15}H_{23}N_5O_4$

Molecular weight 337 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.03 (s, 1H), 7.61 (t, *J* = 1.8 Hz, 1H), 7.43 (t, *J* = 1.8 Hz, 1H), 5.46 (s, 2H), 4.39 (t, *J* = 4.6 Hz, 2H), 4.09 (s, 3H), 3.76 (t, *J* = 4.6 Hz,

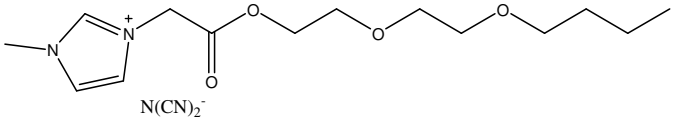
2H), 3.66-3.64 (m, 2H), 3.60-3.57 (m, 2H), 3.43 (t, *J* = 6.9 Hz, 2H), 1.61 (tq, *J* = 6.9, 7.6 Hz, 2H), 0.92 (t, *J* = 7.6 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.15, 138.47, 123.90, 122.90, 73.09, 70.61, 69.92, 68.53, 65.74, 50.23, 36.90, 22.77, 10.53 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2963, 2927, 2863, 2139, 1751, 1635, 1568, 1558 , 1495, 1452, 1217, 1175, 1105

MS *m/z*, 271.3 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(butoxyethoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (186e)



Pale brown solid

The title compound was prepared from 3-methyl-1-(butoxy ethoxy ethoxy carbonyl methyl) imidazolium bromide **186a** (2.92 g, 8.00 mmol) and $NaN(CN)_2$ (0.80 g, 9.00 mmol) according to the general procedure in 98 % yield (2.75 g, 7.83 mmol).

Molecular formula $C_{16}H_{25}N_5O_4$

Molecular weight 351 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 10.23 (s, 1H), 7.41 (t, *J* = 1.8 Hz, 1H), 7.23 (t, *J* = 1.8 Hz, 1H), 5.40 (s, 2H), 4.32 (t, *J* = 4.6 Hz, 2H), 4.01 (s, 3H), 3.68 (t, *J* = 4.6 Hz, 2H), 3.58-3.55 (m, 2H), 3.54-3.50 (m, 2H), 3.39 (t, *J* = 6.7 Hz, 2H), 1.49 (tt, *J* = 6.7, 7.6 Hz, 2H), 1.28 (tq, *J* = 7.6, 7.2 Hz, 2H), 0.85 (t, *J* = 7.2 Hz, 3H)

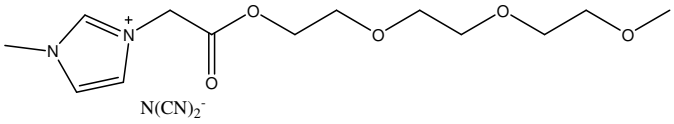
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 164.19, 136.12, 122.00, 121.91, 69.19, 68.58, 67.93, 66.53, 63.70, 48.20, 34.89, 29.63, 17.24, 11.96 Note: C's from anion are not visible in ^{13}C NMR

Mp (°C) 34 – 36 ºC

IR (KBr disc) (cm^{-1}) 3435, 2958, 2867, 2140, 1752, 1635, 1222, 1177, 1100

MS *m/z*, 285.3 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

3-Methyl-1-(methoxyethoxyethoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (187e)



Amber viscous liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy ethoxy carbonylmethyl) imidazolium bromide **187a** (2.94 g, 8.00 mmol) and $NaN(CN)_2$ (0.80 g, 9.00 mmol) according to the general procedure in 75 % yield (2.12 g, 6.01 mmol).

Molecular formula $C_{15}H_{23}N_5O_5$

Molecular weight 353 g/mol

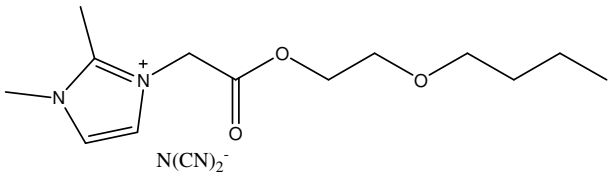
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.72 (s, 1H), 7.67 (d, *J* = 1.6 Hz, 1H), 7.50 (d, *J* = 1.6 Hz, 1H), 5.40 (s, 2H), 4.38 (t, *J* = 4.6 Hz, 2H), 4.07 (s, 3H), 3.74 (t, *J* = 4.6 Hz, 2H), 3.65-3.60 (m, 6H), 3.56-3.53 (m, 2H), 3.37 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.18, 138.18, 124.06, 123.14, 71.79, 70.45, 70.42, 70.35, 68.49, 65.56, 58.88, 50.17, 36.82 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2925, 2859, 2242, 2139, 1751, 1635, 1566, 1558, 1495, 1452, 1217, 1176

MS *m/z*, 287.2 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

2,3-Dimethyl-1-(butoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (190e)



Brown viscous liquid

The title compound was prepared from 2,3-dimethyl-1-(butoxy ethoxy carbonyl methyl) imidazolium bromide **190a** (3.02 g, 9.00 mmol) and $NaN(CN)_2$ (1.07 g, 12.0 mmol) according to the general procedure in 78 % yield (2.25 g, 7.01 mmol).

Molecular formula $C_{15}H_{23}N_5O_3$

Molecular weight 321 g/mol

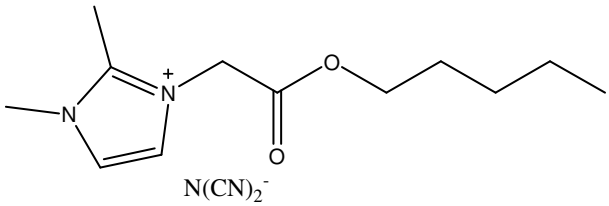
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.71 (d, *J* = 2.0 Hz, 1H), 7.53 (d, *J* = 2.0 Hz, 1H), 5.36 (s, 2H), 4.37 (t, *J* = 4.6 Hz, 2H), 3.95 (s, 3H), 3.67 (t, *J* = 4.6 Hz, 2H), 3.47 (t, *J* = 6.7 Hz, 2H), 2.71 (s, 3H), 1.57 (tt, *J* = 6.7, 7.2 Hz, 2H), 1.37 (tq, *J* = 7.2, 7.5 Hz, 2H), 0.93 (t, *J* = 7.5s Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.13, 145.69, 122.87, 122.47, 71.22, 67.95, 65.78, 49.79, 35.97, 31.60, 19.23, 13.94, 10.78 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2957, 2933, 2864, 2139, 1751, 1635, 1558, 1539, 1495, 1452, 1217, 1120

MS *m/z*, 255.2 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

2,3-Dimethyl-1-(pentoxycarbonylmethyl)imidazolium $N(CN)_2$ (189e)



Yellow oil

The title compound was prepared from 2,3-dimethyl-1-(pentoxy carbonyl methyl) imidazolium bromide **189a** (3.66 g, 12.0 mmol) and $NaN(CN)_2$ (1.78 g, 20.0 mmol) according to the general procedure in 85 % yield (2.96 g, 10.2 mmol).

Molecular formula $C_{14}H_{21}N_5O_2$

Molecular weight 291 g/mol

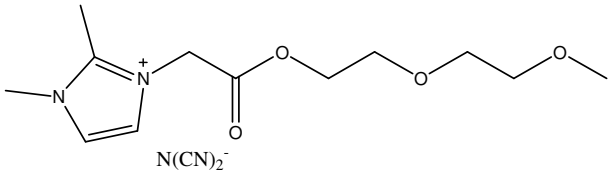
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.70 (d, *J* = 2.0 Hz, 1H), 7.55 (d, *J* = 2.0 Hz, 1H), 5.32 (s, 2H), 4.21 (t, *J* = 7.0 Hz, 2H), 3.95 (s, 3H), 2.71 (s, 3H), 1.68-1.65 (m, 2H), 1.34-1.30 (m, 4H), 0.91 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.15, 145.60, 122.84, 122.47, 67.13, 49.82, 33.99, 28.04, 27.80, 22.23, 13.95, 10.84 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2959, 2933, 2862, 2136, 1751, 1635, 1558, 1539, 1495, 1456, 1228, 1217, 1168

MS *m/z*, 225.2 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

2,3-Dimethyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium $N(CN)_2$ (191e)



Pale brown slightly viscous liquid

The title compound was prepared from 2,3-dimethyl-1-(methoxy ethoxy ethoxy carbonyl methyl) imidazolium bromide **191a** (2.90 g, 8.48 mmol) and $NaN(CN)_2$ (0.84 g, 9.40 mmol) according to the general procedure in 99 % yield (2.74 g, 8.48 mmol).

Molecular formula $C_{14}H_{21}N_5O_4$

Molecular weight 323 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.69 (d, *J* = 2.2 Hz, 1H), 7.51 (d, *J* = 2.2 Hz, 1H), 3.34 (s, 2H), 4.40 (t, *J* = 4.6 Hz, 2H), 3.95 (s, 3H), 3.75 (t, *J* = 4.6 Hz, 2H), 3.66-3.63 (m, 2H), 3.57-3.55 (m, 2H), 3.38 (s, 3H), 2.72 (s, 3H)

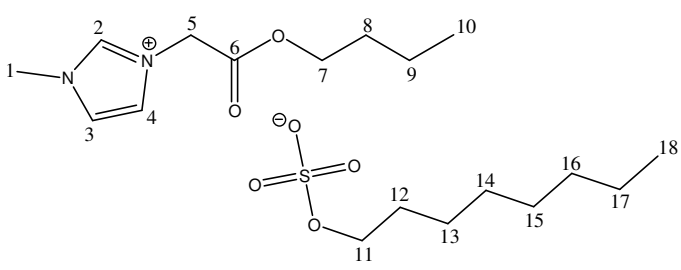
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.09, 145.74, 122.87, 122.46, 71.78, 70.45, 68.45, 65.66, 59.02, 49.73, 35.92, 10.67 Note: C's from anion are not visible in ^{13}C NMR

IR (thin film on salt plate) (cm^{-1}) 2953, 2926, 2859, 2239, 2139, 1751, 1558, 1539, 1495, 1452, 1216, 1103

MS *m/z*, 257.2 $[M\text{-}N(CN)_2^-]^+$; MS: *m/z*, 66.0 $[N(CN)_2^-]$

Achiral $OctOSO_3$ salts

Representative method for the preparation of $OctOSO_3$ salts (3-methyl-1-(butoxycarbonylmethyl)imidazolium $OctOSO_3$) (177f)



To a solution of 3-methyl-1-(butoxy carbonyl methyl) imidazolium bromide **177a** (2.58 g, 9.30 mmol) in distilled water (20 mL) was added in one portion sodium octyl sulfate (1.93 g, 8.30 mmol) and stirred at 60 ºC for 2 h. The water was then slowly removed under vacuum. The precipitate was dissolved in DCM (5 mL) and washed with distilled water (2 x 3 mL). The product remaining was dried

on the rotary evaporator and then under high vacuum for 8 h to give a colourless grease in 61 % yield (2.07 g, 5.09 mmol).

Molecular formula $C_{18}H_{34}N_2O_6S$

Molecular weight 406 g/mol

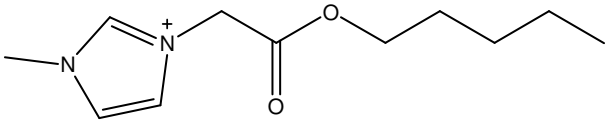
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.40 (s, 1H, *H2*), 7.38 (t, *J* = 1.8 Hz, 1H, *H4*), 7.29 (t, *J* = 1.8 Hz, 2H, *H3*), 5.14 (s, 2H, *H5*), 4.14 (t, *J* = 6.6 Hz, 2H, *H7*), 3.93 (s, 3H, *H1*), 1.63-1.55 (m, 4H, *H's 11 and 8*), 1.36-1.14 (m, 14H, *H's 9 and 12-17*), 0.89 (t, *J* = 7.2 Hz, 3H, *H10*), 0.82 (t, *J* = 6.8 Hz, 3H, *H18*)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.40 (*C*OO), 138.97 (N*C*HN), 123.63 (N*C*H_2), 122.95 (N*C*H_2), 68.07 (O*C*H_2), 66.71 (O*C*H_2), 49.95 (N*C*H_2), 36.60 (*C*H_2), 31.83 (*C*H_2), 30.34 (*C*H_2), 29.47 (*C*H_2), 29.35 (*C*H_2), 29.26 (*C*H_2), 25.86 (*C*H_2), 22.66 (*C*H_2), 18.96 (*C*H_2), 14.12 (*C*H_3), 13.65 (*C*H_3)

IR (thin film on salt plate) (cm^{-1}) 3460, 3115, 2926, 1752, 1569, 1468, 1227, 1060

MS *m/z*, 197.1 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.0 $[OctOSO_3^-]$

3-Methyl-1-(pentoxycarbonylmethyl)imidazolium $OctOSO_3$ (178f)



$OctOSO_3^-$

Pale yellow grease

The title compound was prepared from 3-methyl-1-(pentoxy carbonyl methyl) imidazolium bromide **178a** (2.62 g, 9.00 mmol) and sodium octyl sulfate (1.62 g, 7.00 mmol) according to the general procedure in 96 % yield (2.82 g, 6.70 mmol).

Molecular formula $C_{19}H_{36}N_2O_6S$

Molecular weight 420 g/mol

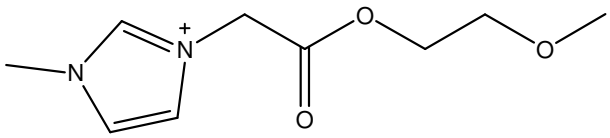
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.51 (s, 1H), 7.36 (t, *J* = 1.6 Hz, 1H), 7.27 (t, *J* = 1.6 Hz, 1H), 5.15 (s, 2H), 4.13 (t, *J* = 7.0 Hz, 2H), 3.94 (m, 5H), 1.61-1.57 (m, 4H), 1.25-1.20 (m, 14H), 0.83-0.78 (m, 6H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.28, 139.22, 123.56, 122.86, 68.01, 67.00, 50.01, 36.60, 31.81, 29.50, 29.33, 29.23, 28.03, 27.81, 25.85, 22.63, 20.01, 14.06, 13.87

IR (thin film on salt plate) (cm^{-1}) 2957, 2926, 2858, 1751, 1558, 1539, 1495, 1452

MS *m/z*, 211.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

3-Methyl-1-(methoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (179f)



$OctOSO_3^-$

Brown grease

The title compound was prepared from 3-methyl-1-(methoxy ethoxy carbonyl methyl) imidazolium bromide **179a** (2.65g, 9.50 mmol) and sodium octyl sulfate (1.97 g, 8.50 mmol) according to the general procedure in 95 % yield (3.30 g, 8.07 mmol).

Molecular formula $C_{17}H_{32}N_2O_7S$

Molecular weight 408 g/mol

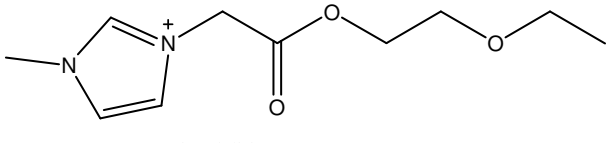
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.51 (s, 1H), 7.44 (s, 1H), 7.33 (s, 1H), 5.25 (s, 2H), 4.30 (t, *J* = 4.6 Hz, 2H), 3.95 (m, 5H), 3.57 (t, *J* = 4.6 Hz, 2H), 3.31 (s, 3H), 1.60 (tt, *J* = 6.8, 7.4 Hz, 2H), 1.29-1.19 (m, 10H), 0.82 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.43, 138.75, 123.75, 122.99, 69.87, 68.10, 65.47, 58.95, 50.05, 36.73, 31.83, 29.45, 29.34, 29.26, 25.85, 22.67, 14.13

IR (thin film on salt plate) (cm^{-1}) 2952, 2925, 2857, 1751, 1558, 1539, 1495, 1452, 1257, 1217, 1176

MS *m/z*, 199.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

3-Methyl-1-(ethoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (180f)



$OctOSO_3^-$

Brown grease

The title compound was prepared from 3-methyl-1-(ethoxy ethoxy carbonyl methyl) imidazolium bromide **180a** (2.93 g, 10.0 mmol) and sodium octyl sulfate (1.86 g, 8.00 mmol) according to the general procedure in 96 % yield (3.24 g, 7.66 mmol).

Molecular formula $C_{18}H_{34}N_2O_7S$

Molecular weight 422 g/mol

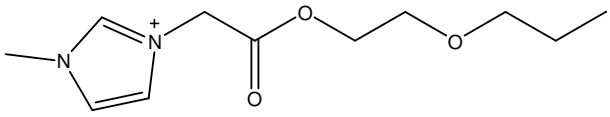
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.42 (s, 1H), 7.37 (s, 1H), 7.28 (s, 1H), 5.17 (s, 2H), 4.29 (t, *J* = 4.7 Hz, 2H), 3.94 (m, 5H), 3.60 (t, *J* = 4.7 Hz, 2H), 3.48 (q, *J* = 7.1 Hz, 2H), 1.63 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.29-1.15 (m, 10H), 1.15 (t, *J* = 7.1 Hz, 3H), 0.82 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.45, 138.89, 123.67, 122.98, 68.23, 67.76, 66.72, 65.70, 49.96, 36.62, 31.83, 29.43, 29.34, 29.26, 25.83, 22.67, 15.07, 14.13

IR (thin film on salt plate) (cm^{-1}) 2955, 2926, 2858, 1751, 1558, 1539, 1495, 1452, 1402, 1217, 1176, 1107

MS *m/z*, 213.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

3-Methyl-1-(propoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (181f)



$OctOSO_3^-$

Dark yellow grease

The title compound was prepared from 3-methyl-1-(propoxy ethoxy carbonyl methyl) imidazolium bromide **181a** (3.68 g, 12.0 mmol) and sodium octyl sulfate (2.09 g, 9.00 mmol) according to the general procedure in 85 % yield (3.33 g, 7.62 mmol).

Molecular formula $C_{19}H_{36}N_2O_7S$

Molecular weight 436 g/mol

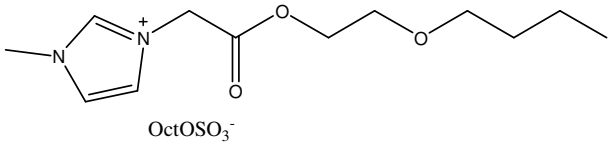
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.45 (s, 1H), 7.48 (t, *J* = 1.6 Hz, 1H), 7.41 (t, *J* = 1.6 Hz, 1H), 5.25 (s, 2H), 4.36 (t, *J* = 4.7 Hz, 2H), 4.01 (m, 5H), 3.67 (t, *J* = 4.7 Hz, 2H), 3.43 (t, *J* = 6.8 Hz, 2H), 1.63-1.58 (m, 4H), 1.56-1.29 (m, 10H), 0.92-0.86 (m, 6H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.45, 138.89, 123.71, 123.06, 73.04, 67.92, 67.89, 65.67, 49.91, 36.58, 31.83, 29.50, 29.36, 29.26, 25.87, 22.73, 22.66, 14.13, 10.47

IR (thin film on salt plate) (cm^{-1}) 3118, 2958, 2927, 2855, 1750, 1569, 1558, 1539, 1495, 1455, 1217, 1178, 1108

MS *m/z*, 227.1 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.0 [$OctOSO_3^-$]

3-Methyl-1-(butoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (182f)



Pale yellow viscous liquid/grease

The title compound was prepared from 3-methyl-1-(butoxy ethoxy carbonyl methyl) imidazolium bromide **182a** (3.15 g, 9.80 mmol) and sodium octyl sulfate (1.81 g, 7.80 mmol) according to the general procedure in 93 % yield (3.27 g, 7.25 mmol).

Molecular formula $C_{20}H_{38}N_2O_7$

Molecular weight 450 g/mol

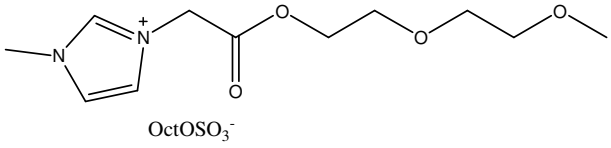
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.49 (s, 1H), 7.36 (t, *J* = 1.6 Hz, 1H), 7.28 (t, *J* = 1.6 Hz, 1H), 5.24 (s, 2H), 4.28 (t, *J* = 4.8 Hz, 2H), 3.94 (m, 5H), 3.59 (t, *J* = 4.8 Hz, 2H), 3.40 (t, *J* = 6.8 Hz, 2H), 1.51 (tt, *J* = 6.8, 6.8 Hz, 2H), 1.28 (tq, *J* = 6.8, 7.1 Hz, 2H), 1.34-1.14 (m, 12H), 0.86 (t, *J* = 7.1 Hz, 3H), 0.80 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.32, 139.12, 123.59, 122.92, 71.25, 67.99, 67.95, 65.78, 49.96, 36.65, 31.84, 31.60, 29.49, 29.36, 29.28, 25.87, 22.68, 19.24, 14.15, 13.95

IR (thin film on salt plate) (cm^{-1}) 3114, 2954, 2927, 2858, 1751, 1567, 1558, 1539, 1495, 1455, 1217, 1112

MS *m/z*, 241.2 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.1 $[OctOSO_3^-]$

3-Methyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (183f)



Yellow grease

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy carbonylmethyl)imidazolium bromide **183a** (3.23 g, 10.0 mmol) and sodium octyl sulfate (2.09 g, 9.00 mmol) according to the general procedure in 82 % yield (3.34 g, 7.37 mmol).

Molecular formula $C_{19}H_{36}N_2O_8$

Molecular weight 452 g/mol

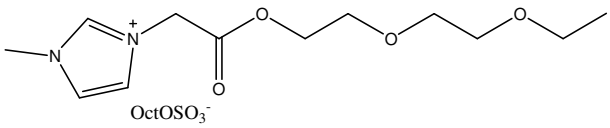
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.23 (s, 1H), 7.47 (t, *J* = 1.8 Hz, 1H), 7.36 (t, *J* = 1.8 Hz, 1H), 5.17 (s, 2H), 4.38 (t, *J* = 4.6 Hz, 2H), 3.92 (m, 5H), 3.67 (t, *J* = 4.6 Hz, 2H), 3.58-3.53 (m, 2H), 3.49-3.44 (m, 2H), 3.30 (s, 3H), 1.60 (tt, *J* = 6.8, 7.4 Hz, 2H), 1.27-1.14 (m, 10H), 0.82 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.67, 138.55, 123.87, 123.14, 71.71, 70.32, 68.58, 68.06, 65.43, 58.96, 49.90, 36.55, 31.84, 29.45, 29.37, 29.27, 25.85, 22.66, 14.13

IR (thin film on salt plate) (cm^{-1}) 2954, 2926, 2859, 1750, 1558, 1539, 1495, 1455, 1401, 1364, 1203, 1174, 1102

MS *m/z*, 243.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

3-Methyl-1-(ethoxyethoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (184f)



Yellow grease

The title compound was prepared from 3-methyl-1-(ethoxy ethoxy ethoxy carbonylmethyl)imidazolium bromide **184a** (3.20 g, 9.50 mmol) and sodium octyl sulfate (1.86 g, 8.00 mmol) according to the general procedure in 93 % yield (3.47 g, 7.21 mmol).

Molecular formula $C_{20}H_{38}N_2O_8S$

Molecular weight 466 g/mol

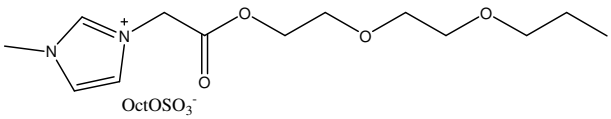
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.44 (s, 1H), 7.52 (s, 1H), 7.40 (s, 1H), 5.23 (s, 2H), 4.37 (t, *J* = 4.8 Hz, 2H), 4.02 (m, 5H), 3.75 (t, *J* = 4.8 Hz, 2H), 3.66-3.63 (m, 2H), 3.61-3.57 (m, 2H), 3.55 (q, *J* = 7.1 Hz, 2H), 1.70 (tt, *J* = 6.8, 7.4 Hz, 2H), 1.38-1.27 (m, 10H), 1.23 (t, *J* = 7.1 Hz, 3H), 0.89 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.46, 138.86, 123.82, 123.01, 70.61, 69.71, 68.57, 68.04, 66.66, 65.63, 49.88, 36.57, 31.82, 29.47, 29.35, 29.26, 25.85, 22.66, 15.15, 14.12

IR (thin film on salt plate) (cm^{-1}) 2957, 2927, 2858, 1751, 1558, 1639, 1495, 1452, 1399, 1260, 1217, 1178, 1106

MS *m/z*, 257.1 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.0 [$OctOSO_3^-$]

3-Methyl-1-(propoxyethoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (185f)



Pale yellow viscous liquid

The title compound was prepared from 3-methyl-1-(propoxy ethoxy ethoxy carbonylmethyl)imidazolium bromide **185a** (0.78 g, 2.23 mmol) and sodium octyl sulfate (0.42 g, 1.80 mmol) according to the general procedure in 98 % yield (0.85 g, 1.77 mmol).

Molecular formula $C_{21}H_{40}N_2O_8$

Molecular weight 480 g/mol

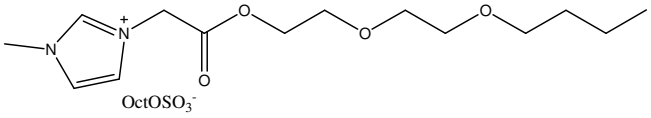
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.41 (s, 1H), 7.45 (t, *J* = 1.8 Hz, 1H), 7.33 (t, *J* = 1.8 Hz, 1H), 5.17 (s, 2H), 4.29 (t, *J* = 4.8 Hz, 2H), 3.94-3.91 (m, 5H), 3.67 (t, *J* = 4.8 Hz, 2H), 3.58-3.54 (m, 2H), 3.53-3.49 (m, 2H), 3.35 (t, *J* = 6.8 Hz, 2H), 1.62-1.48 (m, 14H), 0.85-0.80 (m, 6H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.46, 138.88, 123.82, 123.00, 73.10, 70.58, 70.46, 70.14, 69.93, 67.92, 65.56, 61.82, 36.59, 31.83, 29.49, 29.36, 29.27, 25.87, 22.76, 22.67, 14.13

IR (thin film on salt plate) (cm^{-1}) 2956, 2927, 2859, 1751, 1558, 1539, 1495, 1455, 1217, 1106

MS *m/z*, 271.3 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.1 $[OctOSO_3^-]$

3-Methyl-1-(butoxyethoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (186f)



Pale yellow viscous liquid

The title compound was prepared from 3-methyl-1-(butoxy ethoxy ethoxy carbonyl methyl) imidazolium bromide **186a** (2.19 g, 6.00 mmol) and sodium octyl sulfate (1.16 g, 5.00 mmol) according to the general procedure in 92 % yield (2.28 g, 4.61 mmol).

Molecular formula $C_{22}H_{42}N_2O_8S$

Molecular weight 494 g/mol

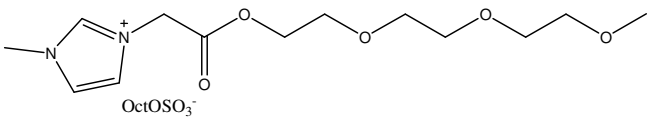
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.34 (s, 1H), 7.50 (t, *J* = 1.8 Hz, 1H), 7.41 (t, *J* = 1.8 Hz, 1H), 5.15 (s, 2H), 4.28 (t, *J* = 4.8 Hz, 2H), 3.93 (m, 5H), 3.67 (t, *J* = 4.8 Hz, 2H), 3.57-3.53 (m, 2H), 3.52-3.48 (m, 2H), 3.38 (t, *J* = 6.8 Hz, 2H), 1.52 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.28 (tq, *J* = 7.2, 6.8 Hz, 2H), 1.32-1.12 (m, 12H), 0.86-0.78 (m, 6H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.48, 138.71, 123.91, 123.16, 71.25, 71.20, 70.56, 68.55, 67.77, 65.52, 49.79, 36.51, 31.81, 31.62, 29.50, 29.35, 29.25, 25.87, 22.64, 19.23, 14.10, 13.93

IR (thin film on salt plate) (cm^{-1}) 2953, 2927, 2859, 1750, 1558, 1539, 1495, 1455, 1217, 1110

MS *m/z*, 285.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.0 [$OctOSO_3^-$]

3-Methyl-1-(methoxyethoxyethoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (187f)



Pale brown viscous liquid

The title compound was prepared from 3-methyl-1-(methoxy ethoxy ethoxy ethoxy carbonyl methyl) imidazolium bromide **187a** (2.20 g, 6.00 mmol) and sodium octyl sulfate (1.62 g, 7.00 mmol) according to the general procedure in 84 % yield (2.51 g, 5.05 mmol).

Molecular formula $C_{21}H_{40}N_2O_9S$

Molecular weight 496 g/mol

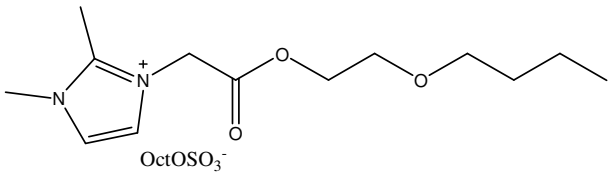
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.36 (s, 1H), 7.44 (t, *J* = 1.6 Hz, 1H), 7.28 (t, *J* = 1.6 Hz, 1H), 5.23 (s, 2H), 4.31 (t, *J* = 4.6 Hz, 2H), 3.96-3.90 (m, 5H), 3.67-3.61 (m, 2H), 3.59-3.53 (m, 6H), 3.29 (s, 3H), 1.61 (tt, *J* = 6.8, 7.4 Hz, 2H), 1.29-1.19 (m, 12H), 0.82 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.77, 138.37, 123.91, 123.25, 70.34, 70.31, 70.26, 70.14, 68.56, 68.04, 65.30, 58.88, 49.86, 36.47, 31.82, 29.42, 29.35, 29.25, 25.83, 22.64, 14.10

IR (thin film on salt plate) (cm^{-1}) 2951, 2926, 2859, 1751, 1566, 1558, 1539, 1495, 1456, 1399, 1217, 1106

MS *m/z*, 287.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

2,3-Dimethyl-1-(butoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (190f)



Beige fluffy solid

The title compound was prepared from 2,3-dimethyl-1-(butoxy carbonyl methyl) imidazolium bromide **190a** (2.51 g, 7.50 mmol) and sodium octyl sulfate (1.51 g, 6.50 mmol) according to the general procedure in 84 % yield (2.53 g, 5.44 mmol).

Molecular formula $C_{21}H_{40}N_2O_7S$

Molecular weight 464 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.49 (d, *J* = 2.2 Hz, 1H), 7.43 (d, *J* = 2.2 Hz, 1H), 5.20 (s, 2H), 4.36 (t, *J* = 4.7 Hz, 2H), 3.88 (m, 5H), 3.67 (t, *J* = 4.7 Hz, 2H), 3.48 (t, *J* = 6.8 Hz, 2H), 2.63 (s, 3H), 1.68-1.55 (m, 4H), 1.42-1.27 (m, 12H), 0.96 (t, *J* = 7.4 Hz, 3H), 0.90 (t, *J* = 7.0 Hz, 3H)

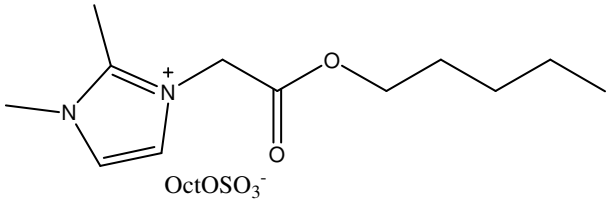
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.52, 145.81, 122.70, 122.40, 71.22, 67.99, 67.82, 65.57, 49.37, 35.57, 31.84, 31.62, 29.49, 29.36, 29.28, 25. 87, 22.67, 19.24, 14.13, 13.94, 10.20

Mp (°C) 50 – 52

IR (KBr disc) (cm^{-1}) 2959, 2927, 2861, 1751, 1558, 1546, 1539, 1495, 1455, 1256, 1217, 1121

MS *m/z*, 255.3 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.1 $[OctOSO_3^-]$

2,3-Dimethyl-1-(pentoxycarbonylmethyl)imidazolium $OctOSO_3$ (189f)



Off-white solid

The title compound was prepared from 2,3-dimethyl-1-(pentoxy carbonyl methyl) imidazolium bromide **189a** (2.47 g, 8.10 mmol) and sodium octyl sulfate (1.65 g, 7.10 mmol) according to the general procedure in 86 % yield (2.66 g, 6.11 mmol).

Molecular formula $C_{20}H_{38}N_2O_6$

Molecular weight 434 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.44 (d, *J* = 2.4 Hz, 1H), 7.36 (d, *J* = 2.4 Hz, 1H), 5.13 (s, 2H), 4.12 (t, *J* = 6.8 Hz, 2H), 3.88 (t, *J* = 7.0 Hz, 2H), 3.81 (s, 3H), 2.57 (s, 3H), 1.64-1.53 (m, 4H), 1.28-1.18 (m, 14H), 0.86 (t, *J* = 7.0 Hz, 3H), 0.82 (t, *J* = 7.0 Hz, 3H)

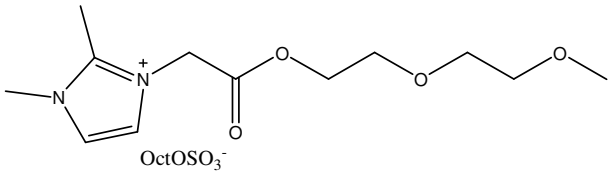
^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.55, 145.82, 122.71, 122.31, 67.59, 66.93, 49.55, 35.64, 31.84, 29.54, 29.37, 29.28, 28.07, 27.83, 25.90, 22.67, 22.24, 14.13, 13.94, 10.45

Mp (°C) 63 – 65

IR (KBr disc) (cm^{-1}) 2956, 2927, 1751, 1452, 1398, 1251, 1219, 1052

MS *m/z*, 225.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

2,3-Dimethyl-1-(methoxyethoxyethoxycarbonylmethyl)imidazolium $OctOSO_3$ (191f)



Yellow grease

The title compound was prepared from 2,3-dimethyl-1-(methoxy ethoxy ethoxy carbonyl methyl) imidazolium bromide **191a** (2.56 g, 7.60 mmol) and sodium octyl sulfate (1.62 g, 7.00 mmol) according to the general procedure in 94 % yield (3.07 g, 6.57 mmol).

Molecular formula $C_{20}H_{38}N_2O_8S$

Molecular weight 466 g/mol

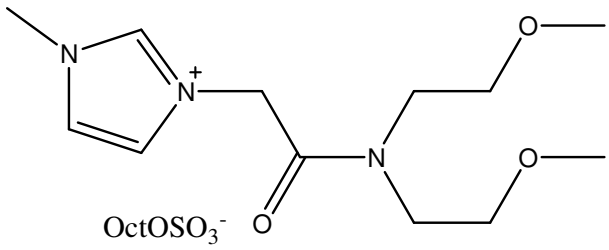
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.48 (d, *J* = 2.0 Hz, 1H), 7.36 (d, *J* = 2.0 Hz, 1H), 5.16 (s, 2H), 4.30 (t, *J* = 4.7 Hz, 2H), 3.91 (t, *J* = 7.0 Hz, 2H), 3.81 (s, 3H), 3.67 (t, *J* = 4.7 Hz, 2H), 3.58-3.52 (m, 2H), 3.48-3.44 (m, 2H), 3.31 (s, 3H), 2.68 (s, 3H), 1.58 (tt, *J* = 6.8, 7.6 Hz, 2H), 1.29-1.15 (m, 10H), 0.82 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 166.55, 145.86, 122.79, 122.35, 71.78, 70.42, 68.56, 67.65, 65.44, 59.04, 49.40, 35.59, 31.83, 29.53, 29.37, 29.28, 25.89, 22.67, 14.13, 10.28

IR (thin film on salt plate) (cm^{-1}) 2955, 2926, 2858, 1751, 1558, 1545, 1539, 1495, 1452, 1217, 1105

MS *m/z*, 257.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

3-Methyl-1-[*bis*-1-methoxyethyl]carbamylmethyl)imidazolium $OctOSO_3$ (205f)



Yellow grease

The title compound was prepared from 3-methyl-1-[(*bis*-1-methoxy ethyl)carbamylmethyl] imidazolium bromide (1.38 g, 4.12 mmol) **205a** and sodium octyl sulfate (4.01 mmol, 0.93 g) according to the general procedure in 92 % yield (1.71 g, 3.67 mmol).

Molecular formula $C_{20}H_{39}N_3O_7S$

Molecular weight 465 g/mol

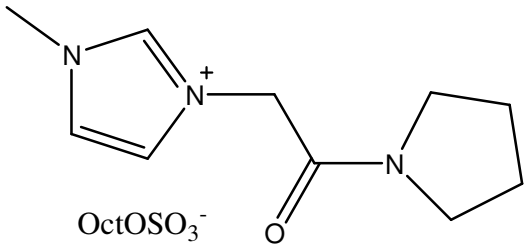
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.34 (s, 1H), 7.25 (t, *J* = 1.6 Hz, 1H), 7.20 (t, *J* = 1.6 Hz, 1H), 5.30 (s, 2H), 3.98 (t, *J* = 6.8 Hz, 2H), 3.91 (s, 3H), 3.60 (t, *J* = 4.8 Hz, 2H), 3.51-3.43 (m, 6H), 3.30 (s, 3H), 3.26 (s, 3H), 1.63 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.30-1.19 (m, 10H), 0.82 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 165.64, 139.03, 124.03, 122.17, 70.54, 70.03, 67.91, 59.17, 58.91, 50.43, 48.62, 46.77, 36.47, 31.83, 29.51, 29.36, 29.27, 25.87, 22.67, 14.13

IR (thin film on salt plate) (cm^{-1}) 3480, 3112, 2926, 1653, 1575, 1472, 1428, 1220, 1119, 1016

MS *m/z*, 256.1 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.0 $[OctOSO_3^-]$

3-Methyl-1 (pyrrolidinecarbonylmethyl)imidazolium bromide $OctOSO_3$ (197f)



White grease

The title compound was prepared from 3-methyl-1-(pyrrolidinyl carbonyl methyl) imidazolium bromide **197a** (7.70 mmol, 2.11 g) and sodium octyl sulfate (8.02 mmol, 1.86 g) according to the general procedure in 97 % yield (3.02 g, 7.48 mmol).

Molecular formula $C_{18}H_{33}N_3O_5S$

Molecular weight 403 g/mol

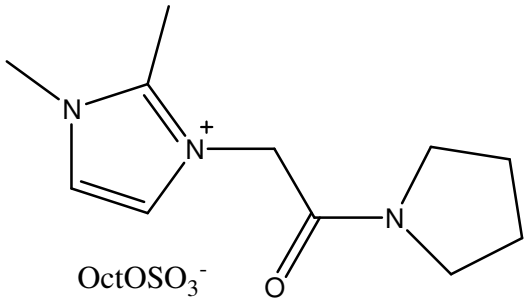
^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 9.53 (s, 1H), 7.45 (t, *J* = 1.8 Hz, 1H), 7.20 (t, *J* = 1.8 Hz, 1H), 5.34 (s, 2H), 3.92 (m, 5H), 3.57 (t, *J* = 6.8 Hz, 2H), 3.40 (t, *J* = 6.8 Hz, 2H), 1.99 (tt, *J* = 6.8, 6.8 Hz, 2H), 1.86 (tt, *J* = 6.8, 6.8 Hz, 2H), 1.61 (tt, *J* = 6.8, 7.4 Hz, 2H), 1.29-1.19 (m, 10H), 0.82 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 162.66, 138.56, 124.32, 122.10, 67.97, 50.84, 46.57, 46.02, 36.58, 31.83, 29.51, 29.36, 29.27, 26.03, 25.87, 24.07, 22.67, 14.14

IR (thin film on salt plate) (cm^{-1}) 3460, 2922, 1652, 1471, 1218, 1089, 979

MS *m/z*, 194.2 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.0 $[OctOSO_3^-]$

2,3-Dimethyl-1 (pyrrolidinecarbonylmethyl)imidazolium $OctOSO_3$ (198f)



Yellow grease

The title compound was prepared from 2,3-dimethyl-1-(pyrrolidinyl carbonyl methyl) imidazolium bromide **198a** (7.46 mmol, 2.15 g) and sodium octyl sulfate (8.02 mmol, 1.86 g) according to the general procedure in 98 % yield (3.06 g, 7.34 mmol).

Molecular formula $C_{19}H_{35}N_3O_5S$

Molecular weight 417 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.52 (d, *J* = 2.0 Hz, 1H), 7.31 (d, *J* = 2.0 Hz, 1H), 5.32 (s, 2H), 3.62 (t, *J* = 6.8 Hz, 2H), 3.82 (s, 3H), 3.38 (t, *J* = 6.8 Hz, 2H), 3.40 (t, *J* = 7.0 Hz, 2H), 2.65 (s, 3H), 1.20 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.85 (tt, *J* = 6.8, 7.2 Hz, 2H), 1.60 (tt, *J* = 6.8, 7.4 Hz, 2H), 1.26-1.15 (m, 10H), 0.82 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 162.79, 145.99, 122.88, 121.79, 67.75, 50.58, 46.47, 45.92, 35.50, 31.82, 29.53, 29.37, 29.27, 26.03, 25.89, 24.07, 22.66, 14.13, 10.52

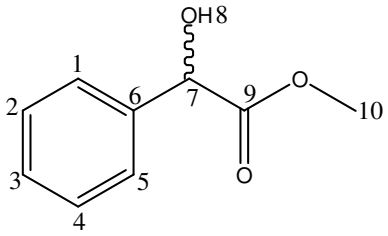
IR (thin film on salt plate) (cm^{-1}) 3460, 2920, 2853, 1651, 1468, 1216, 1116, 1085

MS *m/z*, 208.1 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.0 $[OctOSO_3^-]$

Chapter 3 Experimental

Chiral alcohols

Representative procedure for the preparation of chiral alcohols (*RS* - methyl mandelate) (209o)



A solution of *RS* – mandelic acid (5.32 g, 35.0 mmol) in methanol (11.20 g, 350 mmol) was stirred vigorously under reflux for 6 hours. The progress of the reaction was monitored by TLC. The reaction was cooled and 10 mL of water was added. The product was then extracted with DCM (3 x 5 mL). The product was then dried to give a colourless liquid at RT in 99 % yield (5.75 g, 34.6 mmol).

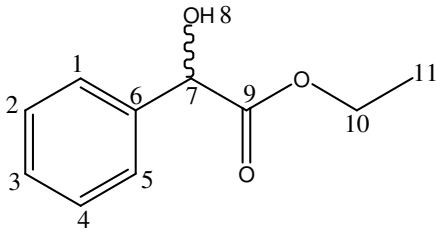
Molecular formula $C_9H_{10}O_3$

Molecular weight 166 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.35-7.24 (m, 5H, *H's 1-5*), 5.10 (s, 1H, *H7*), 3.66 (s, 3H, *H10*), 3.59 (br, 1H, *H8*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 174.16 (*C*O), 138.24 (Ar*C*), 128.65 (Ar*C*), 128.55 (Ar*C*), 126.63 (Ar*C*), 72.93 (*C*OH), 53.05 (O*C*H$_3$)

RS - Ethyl mandelate (209c)



The title compound was prepared from *RS* – mandelic acid (7.81 g, 51.0 mmol) and ethanol (18.4 g, 400 mmol) according to the general procedure in 100 % yield (9.17 g, 51.0 mmol)

Colourless liquid

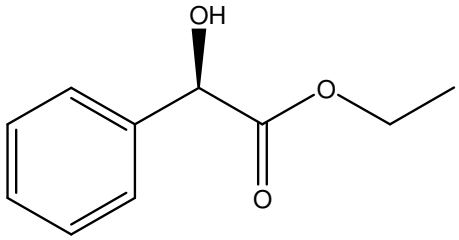
Molecular formula $C_{10}H_{12}O_3$

Molecular weight 180 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.46 (m, 5H, *H's 1-5*), 5.19 (s, 1H, *H7*), 4.33-4.15 (m, 2H, *H10*), 3.50 (br, 1H, *H8*), 1.25 (t, *J* = 7.0 Hz, 3H, *H11*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.72 (*C*O), 138.40 (Ar*C*), 138.71 (Ar*C*), 128.42 (Ar*C*), 126.54 (Ar*C*), 72.89 (*C*OH), 62.28 (O*C*H$_2$), 14.03 (*C*H$_3$)

_R_ - Ethyl mandelate (209a)



The title compound was prepared from *R* – mandelic acid (5.32 g, 35.0 mmol) and ethanol (18.4 g, 400 mmol) according to the general procedure in 98 % yield (6.15 g, 34.2 mmol)

Colourless liquid

Molecular formula $C_{10}H_{12}O_3$

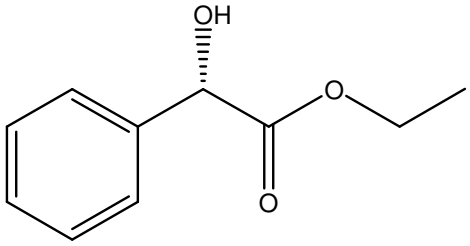
Molecular weight 180 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.48-7.43 (m, 5H), 5.18 (s, 1H,), 4.33-4.15 (m, 2H), 3.45 (br, 1H), 1.27 (t, J = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.72, 138.40, 238.68, 128.58, 126.65, 72.89, 62.29, 14.03

$[\alpha]_D^{20}$ -141.8º (0.7 c, $CHCl_3$)

_S_ - Ethyl mandelate (209b)



The title compound was prepared from *S* – mandelic acid (7.90 g, 52.0 mmol) and ethanol (7.89 g, 172 mmol) according to the general procedure in 84 % yield (7.85 g, 43.6 mmol)

Colourless liquid

Molecular formula $C_{10}H_{12}O_3$

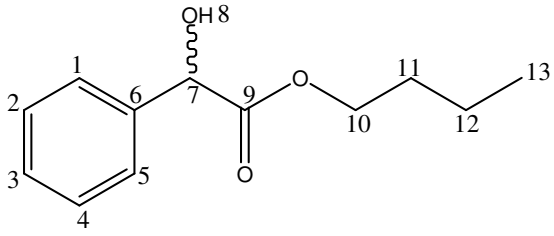
Molecular weight 180 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.49-7.42 (m, 5H), 5.18 (s, 1H), 4.33-4.16 (m, 2H), 3.50 (br, 1H), 1.27 (t, J = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.72, 138.40, 128.63, 128.58, 126.65, 72.90, 62.28, 14.03

$[\alpha]_D^{20}$ +138º (0.7 c, $CHCl_3$)

_RS_ - Butyl mandelate (209f)



Pale yellow liquid

The title compound was prepared from *RS* – mandelic acid (7.60 g, 50.0 mmol) and butanol (10.21 g. 138 mmol) according to the general procedure in 100 % yield (10.38 g, 49.9 mmol)

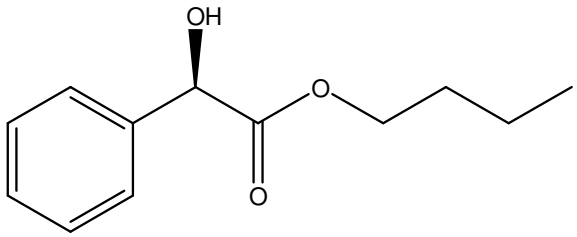
Molecular formula $C_{12}H_{16}O_3$

Molecular weight 208 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.56-7.50 (m, 2H, *H's 1 and 5*), 7.39-7.31 (m, 3H, *H's 2-4*), 5.19 (s, 1H, *H7*), 4.23-4.15 (m, 2H, *H10*), 3.51 (br, 1H, *H8*), 1.62 (tt, *J* = 7.2 Hz, 7.4 Hz, 2H, *H11*), 1.31 (tq, *J* =7.4 Hz, 7.5 Hz, 2H, *H12*), 0.89 (t, *J* = 7.5 Hz, 3H, *H13*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.81 (CO), 138.47 (ArC), 128.39 (Ar*C*), 128.41 (Ar*C*), 126.00 (Ar*C*), 72.88 (*C*OH), 66.03 (O*C*H_2), 30.40 (*C*H_2), 18.85 (*C*H_2), 13.56 (*C*H_3)

_R_ - Butyl mandelate (209d)



Colourless liquid

The title compound was prepared from *R* – mandelic acid (8.82 g, 58.0 mmol) and butanol (10.21 g. 138 mmol) according to the general procedure in 100 % yield (12.01 g, 57.7 mmol)

Molecular formula $C_{12}H_{16}O_3$

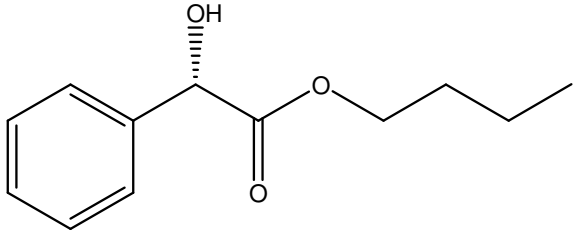
Molecular weight 208 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.46-7.32 (m, 5H), 5.18 (s, 1H), 4.22-4.12 (m, 2H), 2.99 (s, 1H), 1.62 (tt, *J* = 7.0 Hz, 7.2 Hz, 2H), 1.27 (tq, *J* =7.2 Hz, 7.2 Hz, 2H), 0.85 (t, *J* =7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.83, 138.42, 128.55, 128.41, 126.50, 72.85, 66.08, 30.39, 18.85, 13.56

$[\alpha]_D^{20}$ -100.3° (0.6 c, $CHCl_3$)

_S_ - Butyl mandelate (209e)



Colourless liquid

The title compound was prepared from *S* – mandelic acid (8.51 g, 56.0 mmol) and butanol (10.21 g. 138 mmol) according to the general procedure in 98 % yield (11.40 g, 54.8 mmol)

Molecular formula $C_{12}H_{16}O_3$

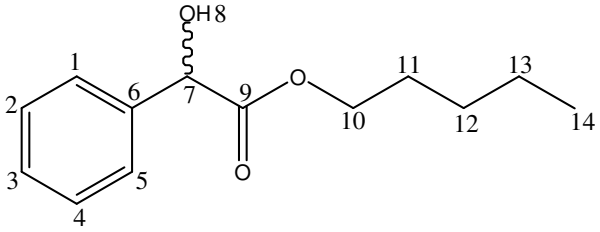
Molecular weight 208 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.46-7.41 (m, 2H), 7.39-7.31 (m, 3H), 5.18 (s, 1H), 4.18-4.08 (m, 2H), 3.32 (s, 1H), 1.58 (tt, *J* = 7.2 Hz, 7.4 Hz, 2H), 1.25 (tq, *J* =7.4 Hz, 7.4 Hz, 2H), 0.89 (t, *J* =7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.82, 138.44, 128.60, 128.54, 126.51, 72.87, 62.74, 30.39, 18.85, 13.55

$[\alpha]_D^{20}$ +88.3º (0.6 c, $CHCl_3$)

_RS_ - Pentyl mandelate (209i)



Pale yellow liquid

The title compound was prepared from *RS* – mandelic acid (7.75 g, 51.0 mmol) and pentanol (13.2 g, 150 mmol) according to the general procedure in 98 % yield (11.1 g, 51.0 mmol)

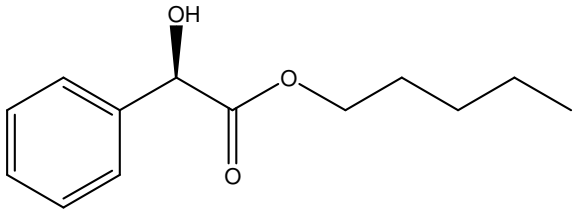
Molecular formula $C_{13}H_{18}O_3$

Molecular weight 222 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.45-7.42 (m, 2H, *H's 1 and 5*), 7.38-7.33 (m, 3H, *H's 2 and 4*), 5.18 (s, 1H, *H7*), 4.17-4.14 (t, *J* = 6.6 Hz, 2H, *H10*), 2.73 (br, 1H, *H8*), 1.63 (tt, *J* = 6.6 Hz, 7.0 Hz, 2H, *H11*), 1.23-1.18 (m, 4H, *H's 12 and 13*), 0.87 (t, *J* =7.0 Hz, 3H, *H14*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.81 (*C*O), 138.48 (Ar*C*), 128.39 (Ar*C*), 126.51 (Ar*C*), 72.87 (Ar*C*), 66.28 (*C*OH), 63.04 (O*C*H_2), 32.44 (*C*H_2), 27.73 (*C*H_2), 22.14 (*C*H_2), 13.88 (*C*H_3)

_R_ - Pentyl mandelate (209g)



Pale yellow liquid

The title compound was prepared from *R* – mandelic acid (7.60 g, 50.0 mmol) and pentanol (13.2 g, 150 mmol) according to the general procedure in 95 % yield (10.6 g, 47.7 mmol)

Molecular formula $C_{13}H_{18}O_3$

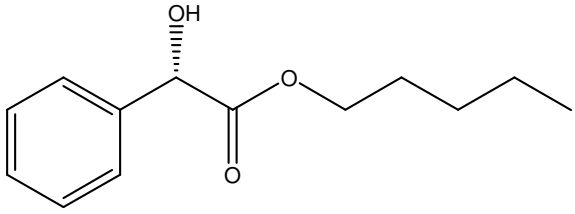
Molecular weight 222 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.46-7.43 (m, 2H), 7.39-7.32 (m, 3H), 5.18 (s, 1H), 4.19 (t, *J* =7.2 Hz, 2H), 3.37 (br, 1H), 1.59 (tt, *J* =7.2 Hz, 7.2 Hz, 2H), 1.35-1.16 (m, 4H), 0.85 (t, *J* =7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.80, 138.50, 128.53, 128.38, 126.53, 72.88, 66.26, 28.01, 27.91, 22.14, 13.89

$[\alpha]_D^{20}$ -99.2º (1.1 c, $CHCl_3$)

_S_ - Pentyl mandelate (209h)



Pale yellow liquid

The title compound was prepared from *S* – mandelic acid (7.60 g, 50.0 mmol) and pentanol (13.2 g, 150 mmol) according to the general procedure in 97 % yield (10.8 g, 48.6 mmol)

Molecular formula $C_{13}H_{18}O_3$

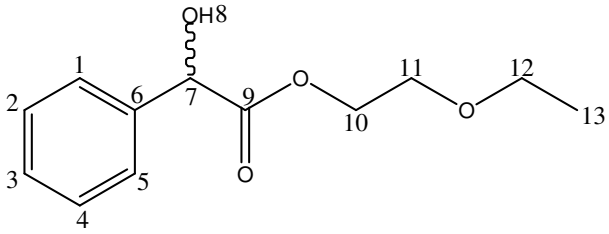
Molecular weight 222 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.46-7.43 (m, 2H), 7.39-7.33 (m, 3H), 5.19 (s, 1H), 4.18 (t, *J* = 7.0 Hz, 2H), 3.05 (br, 1H), 1.59 (tt, *J* = 7.0 Hz, 7.2 Hz, 2H), 1.23-1.15 (m, 4H), 0.85 (t, *J* =7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.82, 138.47, 128.54, 128.40, 126.51, 72.86, 66.31, 27.90, 27.73, 22.14, 13.89

$[\alpha]_D^{20}$ +95.3 (1.0 c, $CHCl_3$)

_RS_ - Ethoxyethyl mandelate (209l)



Pale yellow liquid

The title compound was prepared from *RS* – mandelic acid (8.36 g, 55.0 mmol) and ethoxyethanol (13.95 g, 155 mmol) according to the general procedure in 99 % yield (12.25 g, 54.7 mmol)

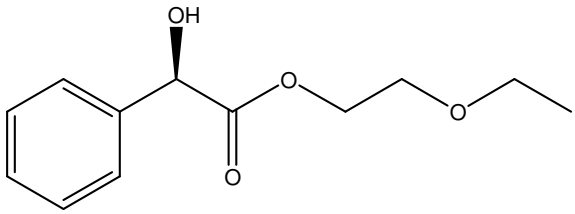
Molecular formula $C_{12}H_{16}O_4$

Molecular weight 224 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.38-7.30 (m, 2H, *H's1 and 5*), 7.29 – 7.22 (m, 3H, *H's 2-4*), 5.12 (s, 1H, *H7*), 4.5 (br, 1H, *H8*), 4.29 – 4.19 (m, 2H, *H10*), 3.57 – 3.50 (m, 2H, *H11*), 3.35 (q, *J* = 6.4 Hz, 2H, *H12*), 0.12 (t, *J* = 6.4 Hz, 3H, *H13*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.66 (*C*O), 138.19 (Ar*C*), 128.55 (Ar*C*), 128.45 (Ar*C*), 126.58 (Ar*C*), 72.88 (*C*OH), 67.93 (O*C*H_2), 65.20 (O*C*H_2), 61.80 (O*C*H_2), 15.10 (*C*H_3)

_R_ - Ethoxyethyl mandelate (209j)



Colourless liquid

The title compound was prepared from *R* – mandelic acid (8.06 g, 53.0 mmol) and ethoxyethanol (13.95 g, 155 mmol) according to the general procedure in 84 % yield (10.23 g, 45.7 mmol)

Molecular formula $C_{12}H_{16}O_4$

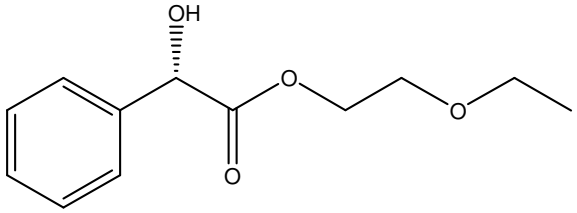
Molecular weight 224 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.47-7.28 (m, 5H), 5.24 (s, 1H), 4.37-4.27 (m, 2H), 3.62 (br, 1H), 3.55 (m, 2H), 3.44 (q, *J* = 6.9 Hz, 2H), 1.16 (t, *J* = 6.9 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 174.00, 139.48, 128.99, 128.67, 127.87, 73.02, 68.71, 67.89, 64.99, 15.00

$[\alpha]_D^{20}$ -94.3° (0.7 c, $CHCl_3$)

_S_ - Ethoxyethyl mandelate (209k)



Colourless liquid

The title compound was prepared from *S* – mandelic acid (8.82 g, 58.0 mmol) and ethoxyethanol (13.95 g, 155 mmol) according to the general procedure in 85 % yield (10.98 g, 49.0 mmol)

Molecular formula $C_{12}H_{16}O_4$

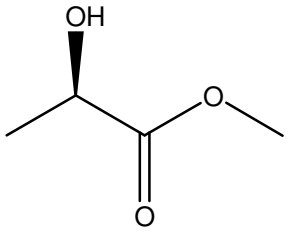
Molecular weight 224 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.46-7.43 (m, 2H), 7.38-7.32 (m, 3H), 5.23 (s, 1H), 4.50 (br, 1H), 4.32-4.27 (m, 2H), 3.58-3.53 (m, 2H), 3.39 (q, *J* = 6.9 Hz, 2H), 1.14 (t, *J* = 6.9 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.57, 138.26, 128.45, 128.42, 126.61, 72.92, 67.91, 66.63, 65.08, 14.97

$[\alpha]_D^{20}$ +96.8º (0.7 c, $CHCl_3$)

_R_ - Methyl lactate (210a)



Colourless liquid

The title compound was prepared from *R* – lactic acid (7.65 g, 85.0 mmol) and methanol (7.04 g, 220 mmol) according to the general procedure in 79 % yield (7.00 g, 67.3 mmol)

Molecular formula $C_4H_8O_3$

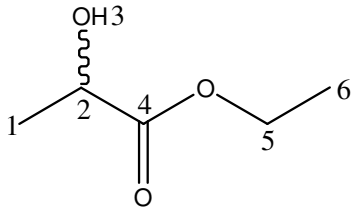
Molecular weight 104 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.32 (q, *J* =7.0 Hz, 1H, *H2*), 3.78 (s, 3H, *H5*), 2.89 (br, 1H, *H3*), 1.43 (d, *J* = 7.0 Hz, 3H, *H1*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 176.53 (*C*O), 66.82 (*C*OH), 52.63 (O*C*H_3), 20.39 (*C*H_3)

$[\alpha]_D^{20}$ -88.2º (0.7 c, $CHCl_3$)

RS - Ethyl lactate (210d)



Colourless liquid

The title compound was prepared from *RS* – lactic acid (27.00 g, 300 mmol) and ethanol (23.0 g, 500 mmol) according to the general procedure in 97 % yield (34.22 g, 290 mmol)

Molecular formula $C_5H_{10}O_3$

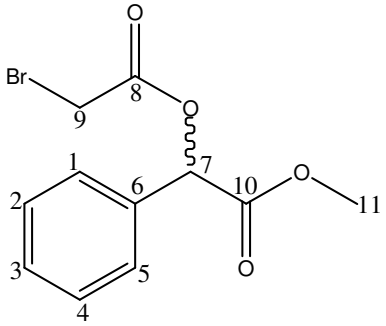
Molecular weight 118 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 4.27 (q, *J* = 7.0 Hz, 3H, *H1*), 3.69 (br, 1H, *H3*), 3.40 (q, *J* = 6.8 Hz, 2H, *H5*), 1.43 (d, *J* = 7.0 Hz, 1H, *H1*), 1.29 (t, *J* = 6.8 Hz, 3H, *H6*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 175.53 (*C*O), 66.64 (*C*OH)), 61.28 (O*C*H_2), 20.12 (*C*H_3), 13.96 (*C*H_3)

Chiral α-bromoestes

Representative procedure for the preparation of chiral mandelyl α-bromoesters (*RS* - methyl mandelyl bromoacetate) (211o)



To a stirred solution of DCM, *RS* - methyl mandelate (1.48 g, 8.92 mmol), and triethylamine (2.02 g, 20.0 mmol), under a nitrogen atmosphere at -78 ºC was added dropwise bromoacetyl bromide (3.03 g, 15.0 mmol). After stirring at -78 ºC for 5 h, the reaction mixture was allowed warm up to -20 ºC and quenched by addition of water (20 mL). The organic phase was washed with distilled water (3 x 20 mL), saturated ammonium chloride (3 x 20 mL), saturated sodium bicarbonate (3 x 20 mL) and brine (2 x 20 mL). The organic phase was then dried over magnesium sulfate, filtered and solvents removed via rotary evaporation to yield a crude product in 84 % yield (2.13 g, 7.42 mmol). Column chromatography was performed on the crude product (mobile phase: DCM:Hexane, 50:50) to give a pale yellow liquid at RT in 73 % yield (1.85 g, 6.45 mmol).

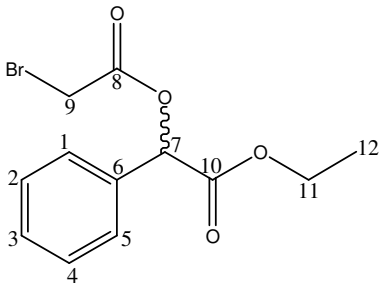
Molecular formula $C_1H_{11}BrO_4$

Molecular weight 287 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.41-7.34 (m, 5H, *H's 1-5*), 5.91 (s, 1H, *H7*), 3.91 (d, J= 1.6 Hz, 2H, *H9*), 3.66 (s, 3H, *H11*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.60 (*C*O), 166.61 (*C*O), 133.00 (Ar*C*), 129.60 (Ar*C*), 128.94 (Ar*C*), 127.68 (Ar*C*), 75.68 (*C*OO), 52.86 (O*C*H_3), 25.32 (*C*H_2)

_RS_ - Ethyl mandelyl bromoacetate (211c)



The title compound was prepared from *RS* – ethyl mandelate (8.64 g, 48.0 mmol) and bromoacetyl bromide (20.20 g, 100 mmol) according to the general procedure in 90 % yield (13.00 g, 43.2 mmol)

Yellow liquid

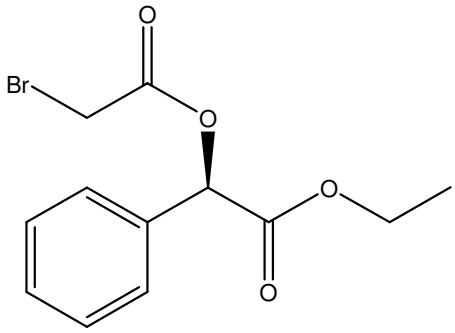
Molecular formula $C_{12}H_{13}BrO_4$

Molecular weight 301 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.51-7.38 (m, 5H, *H's 1-5*), 5.98 (s, 1H, *H7*), 4.30-4.15 (m, 2H, *H11*), 4.00 (d, *J* = 2.0 Hz, 2H, *H9*), 1.27 (t, *J* = 7.0 Hz, 3H, *H12*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.10 (*C*O), 166.62 (*C*O), 133.12 (Ar*C*), 129.49 (Ar*C*), 128.88 (Ar*C*), 127.64 (Ar*C*), 75.83 (*C*OO), 62.02 (O*C*H_2), 25.31 (*C*H_2), 13.99 (*C*H_3)

_R_ - Ethyl mandelyl bromoacetate (211a)



The title compound was prepared from *R* – ethyl mandelate (5.40 g, 30.0 mmol) and bromoacetyl bromide (10.10 g, 50.0 mmol) according to the general procedure in 69 % yield (6.22 g, 20.7 mmol)

Pale yellow liquid

Molecular formula $C_{12}H_{13}BrO_4$

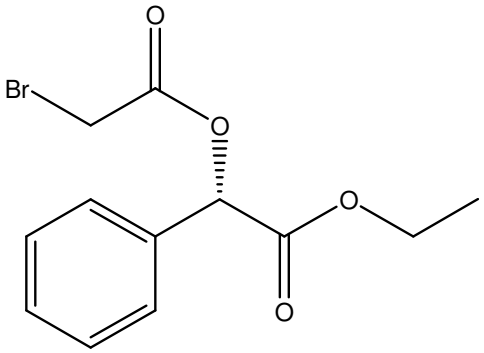
Molecular weight 301 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.50-7.48 (m, 2H), 7.44-7.39 (m, 3H), 5.98 (s, 1H), 4.22-4.09 (m, 2H), 4.00 (d, *J* = 2.4 Hz, 2H), 1.25 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.11, 166.63, 133.09, 129.51, 128.89, 127.64, 75.83, 62.04, 25.34, 14.00

$[\alpha]_D^{20}$ -103.1º (0.7 c, $CHCl_3$)

_S_ - Ethyl mandelyl bromoacetate (211b)



The title compound was prepared from *S* – ethyl mandelate (7.92 g, 44.0 mmol) and bromoacetyl bromide (16.16 g, 80.0 mmol) according to the general procedure in 66 % yield (8.73 g, 29.0 mmol)

Colourless liquid

Molecular formula $C_{12}H_{13}BrO_4$

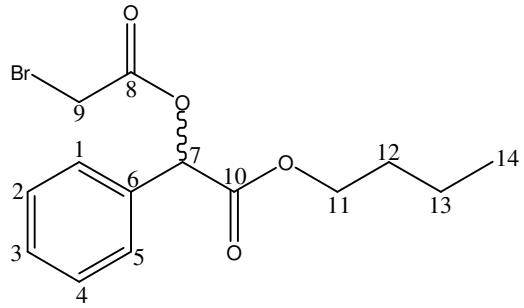
Molecular weight 301 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.51-7.39 (m, 5H), 5.98 (s, 1H), 4.30-4.15 (m, 2H), 4.00 (d, *J* = 2.0 Hz, 2H), 1.27 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.10, 166.62, 133.12, 129.49, 128.88, 127.64, 75.83, 62.02, 25.32, 13.99

$[\alpha]_D^{20}$ +100 (0.7 c, $CHCl_3$)

_RS_ - Butyl mandelyl bromoacetate (211f)



The title compound was prepared from *RS* – butyl mandelate (10.41 g, 50.0 mmol) and bromoacetyl bromide (16.16 g, 80.0 mmol) according to the general procedure in 75 % yield (12.31 g, 37.4 mmol)

Colourless liquid

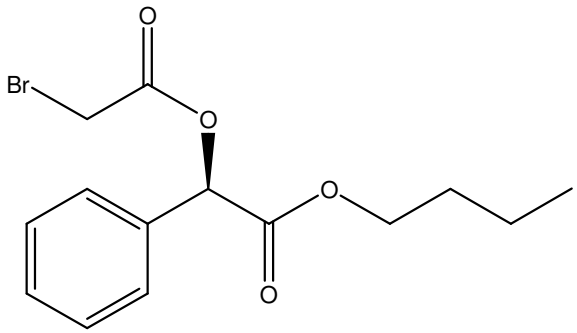
Molecular formula $C_{14}H_{17}BrO_4$

Molecular weight 329 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.49-7.46 (m, 2H, *H's 1 and 5*), 7.45-7.40 (m, 3H, *H's 2-4*), 5.98 (s, 1H, *H7*), 4.22-4.11 (m, 2H, *H11*), 4.00 (d, *J* =2.0 Hz, 2H, *H9*), 1.62-1.55 (m, 2H, *H12*), 1.30 (tq, *J* = 7.4 Hz, 7.4 Hz, 2H, *H13*), 0.88 (t, *J* =7.4 Hz, 3H, *H14*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.18 (*C*O), 166.61 (*C*O), 133.16 (Ar*C*), 129.48 (Ar*C*), 128.86 (Ar*C*), 127.60 (Ar*C*), 75.82 (*C*OO), 65.79 (O*C*H_2), 30.37 (*C*H_2), 25.34 (*C*H_2), 18.87 (*C*H_2), 13.58 (*C*H_3)

_R_ - Butyl mandelyl bromoacetate (211d)



The title compound was prepared from *R* – butyl mandelate (12.48 g, 60.0 mmol) and bromoacetyl bromide (13.33, 66.0 mmol) according to the general procedure in 80 % yield (15.87 g, 48.24 mmol)

Pale yellow liquid

Molecular formula $C_{14}H_{17}BrO_4$

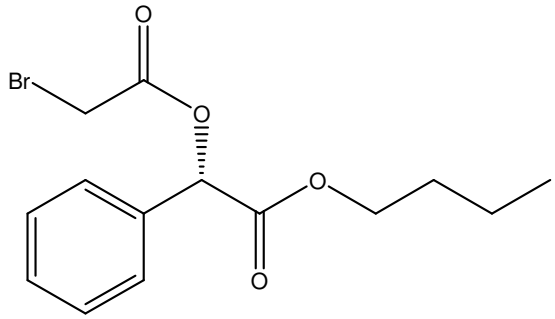
Molecular weight 329 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.49-7.45 (m, 2H), 7.42-7.38 (m, 3H), 5.98 (s, 1H), 4.17-4.08 (m, 2H), 4.00 (d, *J* =1.6 Hz, 2H), 1.60-1.55 (m, 2H), 1.30 (tq, *J* =7.6 Hz, 7.3 Hz, 2H), 0.88 (t, *J* =7.3 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.19, 166.62, 133.17, 129.30, 128.86, 128.63, 75.83, 65.79, 30.38, 25.35, 18.88, 13.59

$[\alpha]_D^{20}$ -91.2º (0.6 c, $CHCl_3$)

_S_ - Butyl mandelyl bromoacetate (211e)



The title compound was prepared from *S* – butyl mandelate (8.32 g, 40.0 mmol) and bromoacetyl bromide (12.12 g, 60.0 mmol) according to the general procedure in 69 % yield (9.08 g, 27.60 mmol)

Yellow liquid

Molecular formula $C_{14}H_{17}BrO_4$

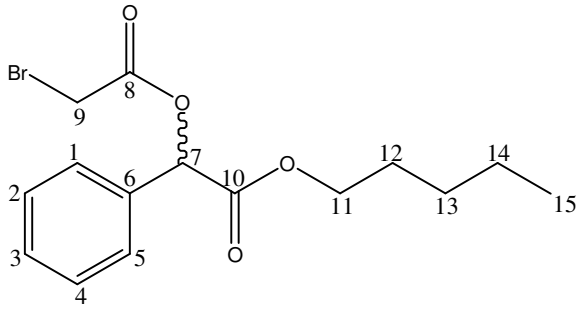
Molecular weight 329 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.49-7.46 (m, 2H), 7.42-7.39 (m, 3H), 5.98 (s, 1H), 4.17-4.07 (m, 2H), 4.00 (d, *J* = 2.0 Hz, 2H), 1.60-1.57 (m, 2H), 1.28 (tq, *J* = 7.4 Hz, 7.6 Hz, 2H), 0.88 (t, *J* = 7.6 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.00, 168.85, 135.40, 129.48, 128.86, 127.60, 75.82, 65.79, 30.37, 25.32, 18.87, 13.57

$[\alpha]_D^{20}$ +89.8º (0.6 c, $CHCl_3$)

_RS_ - Pentyl mandelyl bromoacetate (211i)



The title compound was prepared from *RS* – pentyl mandelate (5.33 g, 24.0 mmol) and bromoacetyl bromide (8.08 g, 40.0 mmol) according to the general procedure in 63 % yield (5.21 g, 15.2 mmol)

Pale yellow liquid

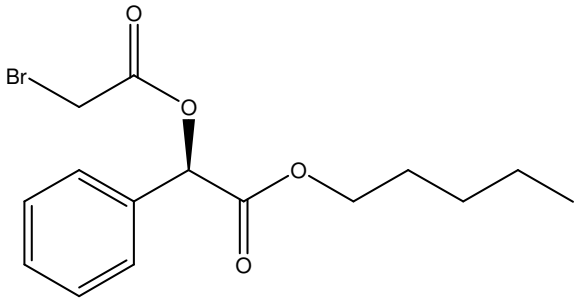
Molecular formula $C_{15}H_{19}BrO_4$

Molecular weight 343 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.41-7.37 (m, 5H, *H's 1-5*), 5.89 (s, 1H, *H7*), 4.08 (t, *J* = 6.7 Hz, 2H, *H11*), 3.91 (d, *J* = 2.0 Hz, 2H, *H9*), 1.56 (tt, *J* = 6.7 Hz, 7.2 Hz, 2H, *H12*), 1.23-1.20 (m, 4H, *H's 13 and 14*), 0.78 (t, *J* = 7.0 Hz, 3H, *H15*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.13 (*C*O), 165.55 (*C*O), 132.16 (Ar*C*), 128.43 (Ar*C*), 127.81 (Ar*C*), 126.56 (Ar*C*), 74.78 (*C*OO), 64.99 (O*C*H_2), 27.01 (*C*H_2), 26.70 (*C*H_2), 24.28 (*C*H_2), 21.11 (*C*H_2), 12.86 (*C*H_3)

_R_ - Pentyl mandelyl bromoacetate (211g)



The title compound was prepared from *R* – pentyl mandelate (10.43 g, 47.0 mmol) and bromoacetyl bromide (14.14 g, 70.0 mmol) according to the general procedure in 57 % yield (9.21 g, 26.9 mmol)

Pale yellow liquid

Molecular formula $C_{15}H_{19}BrO_4$

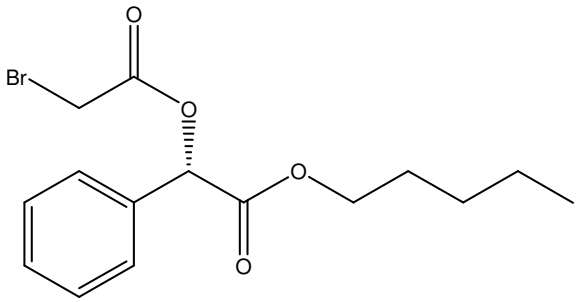
Molecular weight 343 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.40-7.34 (m, 2H), 7.33-7.28 (m, 3H), 5.89 (s, 1H), 4.06 (t, *J* = 7.0 Hz, 2H), 3.91 (d, *J* =1.6 Hz, 2H), 1.51 (tt, *J* = 7.0 Hz, 7.2 Hz, 2H), 1.50-1.37 (m, 4H), 0.77 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.18, 166.60, 133.18, 129.48, 128.85, 127.61, 75.82, 66.04, 28.05, 27.74, 25.33, 22.15, 13.91

$[\alpha]_D^{20}$ -80.3º (0.6 c, $CHCl_3$)

_S_ - Pentyl mandelyl bromoacetate (211h)



The title compound was prepared from *S* – pentyl mandelate (11.10 g, 50.0 mmol) and bromoacetyl bromide (14.14 g, 70.00 mmol) according to the general procedure in 37 % yield (6.33 g, 18.5 mmol)

Colourless liquid

Molecular formula $C_{15}H_{19}BrO_4$

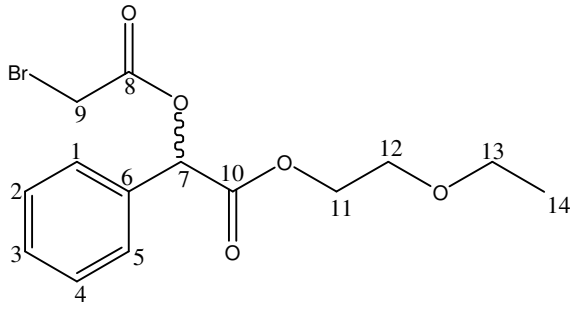
Molecular weight 343 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.50-7.43 (m, 2H), 7.42-7.35 (m, 3H), 5.98 (s, 1H), 4.16-4.10 (t, *J* = 6.8 Hz, 2H), 4.01 (d, *J* = 2.0 Hz, 2H), 1.62 (tt, *J* = 6.8 Hz, 7.0 Hz, 2H), 1.25-1.18 (m, 4H), 0.86 (t, *J* =7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.18, 166.60, 133.19, 129.48, 128.86, 127.61, 75.82, 66.04, 28.05, 27.74, 25.33, 22.15, 13.91

$[\alpha]_D^{20}$: +89.3º (0.5 c, $CHCl_3$)

RS - Ethoxyethyl mandelyl bromoacetate (211l)



Pale yellow liquid

The title compound was prepared from *RS* – ethoxyethyl mandelate (12.10 g, 54.0 mmol) and bromoacetyl bromide (12.12 g, 60.00 mmol) according to the general procedure in 65 % yield (12.11 g, 35.1 mmol)

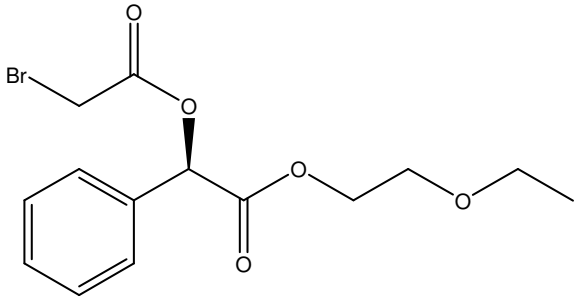
Molecular formula $C_{14}H_{17}BrO_5$

Molecular weight 345 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.50-7.47 (m, 2H, *H's 1 and 5*), 7.42-7.34 (m, 3H, *H's 2-4*), 6.02 (s, 1H, *H7*), 4.31 (t, *J* = 4.8 Hz, 2H, *H12*), 4.00 (d, *J* = 2.0 Hz, 2H, *H9*), 3.59 (t, *J* = 4.8 Hz, 2H, *H13*), 3.43 (q, *J* = 7.2 Hz, 2H, *H14*), 1.16 (t, *J* = 7.2 Hz, 3H, *H15*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.10 (*C*O), 166.59 (*C*O), 132.94 (Ar*C*), 129.33 (Ar*C*), 128.85 (Ar*C*), 127.70 (Ar*C*), 75.73 (*C*OO), 67.92 (O*C*H_2), 66.61 (O*C*H_2), 64.98 (*C*H_3), 25.34 (*C*H_2), 15.06 (*C*H_3)

R - Ethoxyethyl mandelyl bromoacetate (211j)



Pale yellow liquid

The title compound was prepared from *R* – ethoxyethyl mandelate (8.51 g, 38.0 mmol) and bromoacetyl bromide (10.10 g, 50.0 mmol) according to the general procedure in 76 % yield (9.94 g, 28.8 mmol)

Molecular formula $C_{14}H_{17}BrO_5$

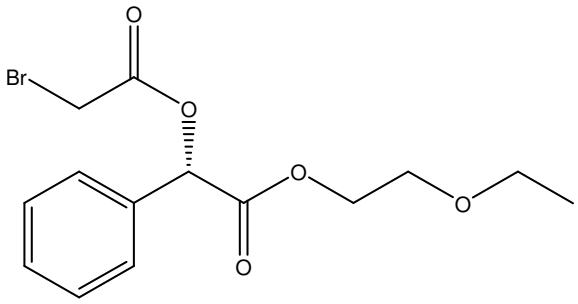
Molecular weight 345 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.43-7.36 (m, 5H), 5.93 (s, 1H), 4.24 (t, *J* = 4.8 Hz, 2H), 3.91 (d, *J* = 1.6 Hz, 2H), 3.54 (t, *J* = 4.8 Hz, 2H), 3.36 (q, *J* = 6.9 Hz, 2H), 1.07 (t, *J* = 6.9 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.09, 166.58, 132.95, 129.52, 128.85, 127.70, 75.73, 67.92, 66.60, 64.99, 25.34, 15.07

$[\alpha]_D^{20}$ -79.2º (0.7 c, $CHCl_3$)

_S_ - Ethoxyethyl mandelyl bromoacetate (211k)



Yellow liquid

The title compound was prepared from *S* – ethoxyethyl mandelate (12.10 g, 54.0 mmol) and bromoacetyl bromide (12.12 g, 60.0 mmol) according to the general procedure in 65 % yield (12.11 g, 35.1 mmol)

Molecular formula $C_{14}H_{17}BrO_5$

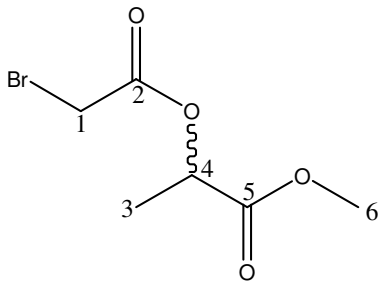
Molecular weight 345 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.51-7.47 (m, 2H), 7.42-7.35 (m, 3H), 6.02 (s, 1H), 4.31 (t, *J* = 4.8 Hz, 2H), 4.00 (d, *J* = 1.6 Hz, 2H), 3.59 (t, *J* = 4.8 Hz, 2H), 3.43 (q, *J* = 7.1 Hz, 2H), 1.14 (t, *J* = 7.1 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.10, 166.58, 132.95, 129.52, 128.85, 127.70, 75.73, 67.92, 66.60, 64.99, 25.34, 15.07

$[\alpha]_D^{20}$ +83.5º (0.5 c, $CHCl_3$)

Representative procedure for the preparation of chiral lactate α-bromoesters (*RS* – methyl lactyl bromoacetate) (212b)



To a stirred solution of DCM, *RS* - methyl lactate (3.95 g, 38.0 mmol), and triethylamine (20.20 g, 200 mmol), under a nitrogen atmosphere at -78 ºC was added dropwise bromoacetyl bromide (16.16 g, 80.0 mmol). After stirring at -78 ºC for 4 h and – 20 ºC for 2 h, the reaction mixture was quenched by addition of water (60 mL). The organic phase was washed with distilled water (3 x 30 mL), saturated ammonium chloride (3 x 30 mL), saturated sodium bicarbonate (3 x 30 mL) and brine (2 x 30 mL). The organic phase was then dried over magnesium sulfate, filtered and solvents removed via rotary evaporation to yield a crude product in 99 % yield (8.44 g, 37.5 mmol). The crude product was distilled under high vacuum and 3 fractions were obtained. The first two fractions contained residual starting material,

but the third fraction was obtained pure as a clear liquid at RT in 37 % yield (3.17 g, 14.1 mmol).

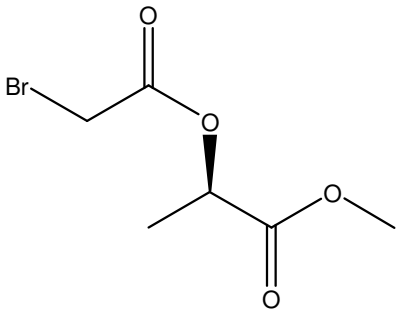
Molecular formula $C_6H_9BrO_4$

Molecular weight 225 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 5.16 (q, *J* = 7.3 Hz, 1H, *H4*), 3.90 (s, 2H, *H1*), 3.72 (s, 3H, *H6*), 1.53 (d, *J* = 7.3 Hz, 3H, *H3*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 170.47 (*C*O), 166.64 (*C*O), 70.05 (O*C*H), 52.55 (O*C*H_3), 25.31 (*C*H_2), 16.78 (*C*H_3)

_R_ – Methyl lactyl bromoacetate (212a)



The title compound was prepared from *R* – methyl lactate (3.95 g, 38.0 mmol) and bromoacetyl bromide (20.2 g, 100 mmol) according to the general procedure in 59 % yield (5.01 g, 22.2 mmol)

Colourless liquid

Molecular formula $C_6H_9BrO_4$

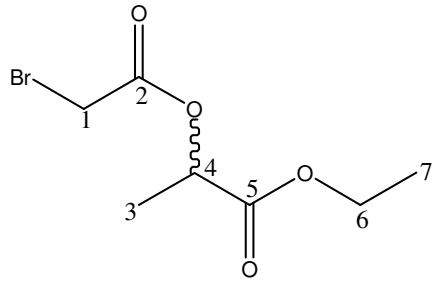
Molecular weight 225 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 5.12 (q, *J* = 7.2 Hz, 1H), 3.85 (s, 2H), 3.70 (s, 3H), 1.48 (d, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 170.40, 166.58, 69.95, 52.50, 25.29, 16.78

$[\alpha]_D^{20}$ -102º (0.6 c, $CHCl_3$)

_RS_ – Ethyl lactyl bromoacetate (212d)



Pale yellow liquid

The title compound was prepared from *RS* – ethyl lactate (16.64 g, 141.0 mmol) and bromoacetyl bromide (40.4 g, 200.0 mmol) according to the general procedure in 57 % yield (19.10 g, 79.91 mmol)

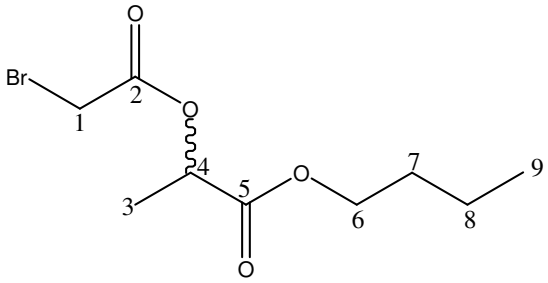
Molecular formula $C_7H_{11}BrO_4$

Molecular weight 239 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 5.17(q, *J* = 7.2 Hz, 1H, *H4*), 4.25(q, *J* = 7.2 Hz, 2H, *H6*), 3.92(s, 2H, *H1*), 1.55(d, J= 7.2 Hz, 3H, *H3*), 1.31(t, J= 7.2 Hz, 3H, *H7*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 170.05 (*C*O), 166.69 (*C*O), 70.16 (O*C*H), 61.67 (O*C*H_2), 25.33 (*C*H_2), 16.74 (*C*H_3), 14.06 (*C*H_3)

_RS_ – Butyl lactyl bromoacetate (212h)



Pale yellow liquid

The title compound was prepared from *RS* – butyl lactate (6.86 g, 47.0 mmol) and bromoacetyl bromide (10.10 g, 50.0 mmol) according to the general procedure in 40 % yield (4.99 g, 18.69 mmol)

Molecular formula $C_9H_{15}BrO_4$

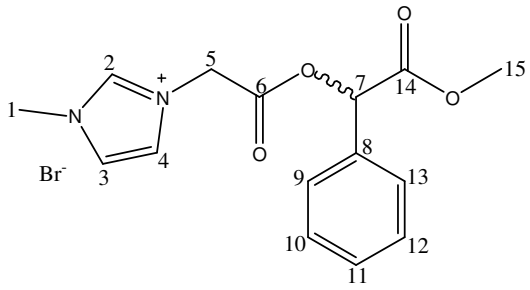
Molecular weight 267 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 5.16 (q, *J* = 7.2 Hz, 1H, *H4*), 4.18 (t, *J* = 6.8 Hz, 2H, *H6*), 3.93 (s, 2H, *H1*), 1.68-1.61 (m, 2H, *H7*), 1.55 (d, *J* = 7.2 Hz, 3H, *H4*), 1.44-1.34 (m, 2H, *H8*), 0.95 (t, *J* = 7.4 Hz, 3H, *H9*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 170.17 (*C*O), 166.71 (*C*O), 70.19 (O*C*H), 65.53 (O*C*H_2), 30.47 (*C*H_2), 25.36 (*C*H_2), 19.01 (*C*H_3), 16.81 (*C*H_2), 13.67 (*C*H_3)

Chiral Bromide salts

Representative procedure for the preparation of chiral bromide salts (*RS* - 3-methyl-1-(methylmandelylcarbonylmethyl)imidazolium bromide) (213o)



To a stirred solution of 1-methylimidazole (18.0 mmol, 1.48 g) in diethyl ether (100 mL) at -15 ºC under a nitrogen atmosphere was added drop wise *RS* - methyl mandelyl bromoacetate (20.0 mmol, 5.74 g). The reaction mixture was stirred vigorously at -15 ºC for 4 h, then at RT overnight. The ether top phase was decanted and the product washed with ether (3 x 10 mL), the solvent removed on the rotary evaporator and dried under high vacuum for 8 h to give an off-white powder at RT in 94 % yield (6.90 g, 18.7 mmol).

Molecular formula $C_{15}H_{17}BrN_2O_4$

Molecular weight 369 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.25 (s, 1H, *H2*), 7.61 (s, 1H, *H4*), 7.47 (s, 1H, *H3*), 7.45-7.50 (m, 5H, *H's 9-13*), 6.02 (s, 1H, *H7*), 5.81 (d, *J* = 17.6 Hz, 1H, *H5*), 5.56 (d, *J* = 17.6 Hz, 1H, *H5*), 4.05 (s, 3H, *H1*), 3.72 (s, 3H, *H15*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.46 (*C*O), 165.76 (*C*O), 138.56 (N*C*H_2N), 132.29 (Ar*C*), 129.88 (Ar*C*), 129.06 (Ar*C*), 127.86 (Ar*C*), 123.72 (N*C*H_2), 123.05 (N*C*H_2), 76.23 (O*C*H), 53.09 (N*C*H_2), 50.22 (O*C*H_3), 36.95 (N*C*H_3)

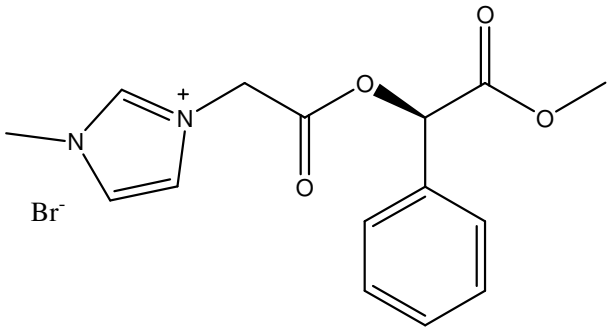
MP (°C)140 – 142

IR (KBr disc) (cm^{-1}) 3482, 3393, 3088, 1762, 1744, 1576, 1565, 1453, 1436, 1380, 1285, 1231, 1213, 1174, 1019

MS m/z, Found 289.1185 [M-Br-]$^+$, Calcd. $C_{18}H_{23}N_2O_4$ 289.1188

MS *m/z*, 289.1 [M-Br^-]$^+$; MS: *m/z*, 79 and 81 [Br^-]

_R_ - 3-Methyl-1-(methylmandelylcarbonylmethyl)imidazolium bromide (213m)



The title compound was prepared from *R* – mandelate bromoacetate (11.48 g, 40.0 mmol) and 1-methylimidazole (3.12 g, 38.0 mmol) according to the general procedure in 93 % yield (12.97 g, 35.2 mmol)

Beige solid

Molecular formula $C_{15}H_{17}BrN_2O_4$

Molecular weight 369 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.03 (s, 1H), 7.59 (s, 1H), 7.48 (s, 1H), 7.37-7.31 (m, 5H), 5.93 (s, 1H), 5.70 (d, *J* = 17.6 Hz, 1H), 5.50 (d, *J* = 17.6 Hz, 1H), 3.96 (s, 3H), 3.63 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.50, 165.88, 138.22, 132.35, 129.84, 129.05, 127.85, 123.76, 123.28, 76.17, 53.09, 50.18, 36.94

MP (°C) 99 – 101

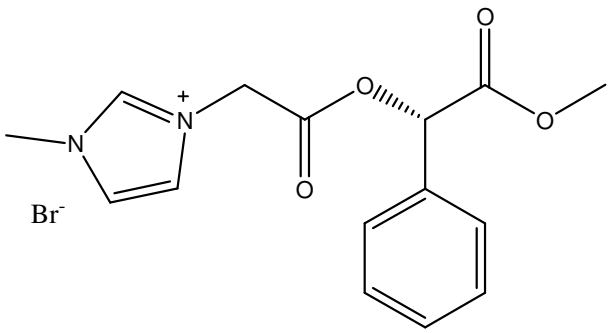
IR (KBr disc) (cm^{-1}) 3477, 3393, 3090, 1761, 1746, 1577, 1564, 1452, 1432, 1380, 1285 1233, 1218, 1176, 1022

MS m/z, Found 289.1180 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{18}H_{23}N_2O_4$ 289.1188

MS *m/z*, 289.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$ -62.7º (0.57 c, $CHCl_3$)

_S_ - 3-Methyl-1-(methylmandelylcarbonylmethyl)imidazolium bromide (213n)



The title compound was prepared from *S* – mandelate bromoacetate (10.05 g, 35.0 mmol) and 1-methylimidazole (2.62 g, 32.0 mmol) according to the general procedure in 78 % yield (10.10 g, 27.4 mmol)

Off-white solid

Molecular formula $C_{15}H_{17}BrN_2O_4$

Molecular weight 369 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.16 (s, 1H), 7.53 (t, *J* = 1.8 Hz, 1H), 7.39 (t, *J* = 1.8 Hz, 1H), 7.387.32 (m ,5H), 5.94 (s, 1H), 5.73 (d, *J* = 18.0 Hz, 1H), 5.49 (d, J= 18.0 Hz, 1H), 3.98 (s, 3H), 3.66 (s, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.48, 165.85, 138.34, 132.23, 129.85, 129.05, 127.85, 123.76, 123.21, 76.19, 53.08, 50.20, 15.29

MP (°C) 97 – 99

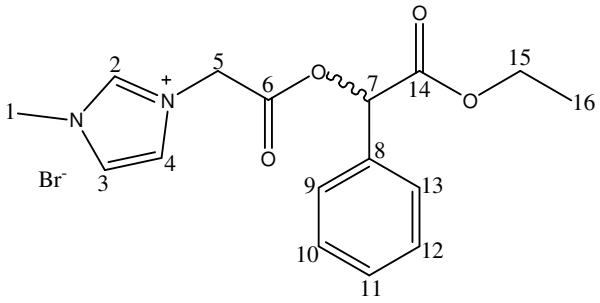
IR (KBr disc) (cm^{-1}) 3481, 3393, 3086, 2949, 1763, 1744, 1577, 1566, 1452, 1434, 1380, 1285, 1231, 1213, 1174 1018

MS m/z, Found 289.1181 [M-Br-]$^+$, Calcd. $C_{18}H_{23}N_2O_4$ 289.1188

MS *m/z*, 289.1 [M-Br^-]$^+$; MS: *m/z*, 79 and 81 [Br^-]

$[\alpha]_D^{20}$ +63.8º (0.59 c, $CHCl_3$)

_RS_ - 3-Methyl-1-(ethylmandelylcarbonylmethyl)imidazolium bromide (213c)



Beige powder

The title compound was prepared from *RS* – ethyl mandelyl bromoacetate (24.0 mmol, 7.22 g) and 1-methylimidazole (21.0 mmol, 1.72 g) according to the general procedure in 68 % yield (5.48 g, 14.3 mmol)

Molecular formula $C_{15}H_{17}BrN_2O_4$

Molecular weight 383 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.99 (s, 1H, *H2*), 7.56 (t, *J* = 1.7 Hz, 1H, *H4*), 7.47 (t, *J* = 1.7 Hz, 1H, *H3*), 7.34-7.30 (m, 5H, *H's 9-13*), 5.91 (s, 1H, *H1*), 5.69 (d, *J* = 17.8 Hz, 1H, *H5*), 5.48 (d, *J* = 17.8 Hz, 1H, *H5*), 4.10-4.01 (m, 2H, *H15*), 3.96 (s, 3H, *H7*), 1.14 (t, *J* = 7.2 Hz, 3H, *H16*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.96 (*C*O), 165.77 (*C*O), 138.34 (N*C*H_2N), 132.44 (Ar*C*), 129.76 (Ar*C*), 129.00 (Ar*C*), 127.80 (Ar*C*), 123.72 (N*C*H_2), 123.21 (N*C*H_2), 76.31 (O*C*H), 62.26 (N*C*H_2), 50.19 (O*C*H_2), 36.93 (N*C*H_3), 13.99 (*C*H_3)

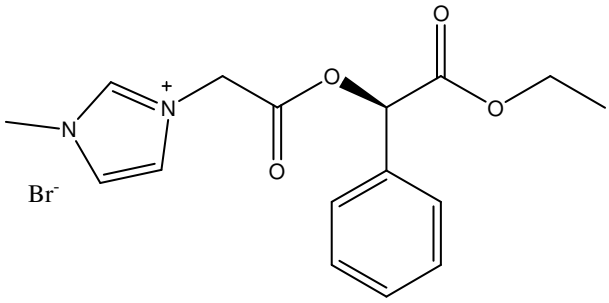
MP (°C)132 – 134

IR (KBr disc) (cm^{-1}) 2963, 2928, 1751, 1559, 1539, 1495, 1452, 1403, 1370, 1215, 1177

MS m/z, Found 303.1349 [M-Br-]$^+$, Calcd. $C_{16}H_{19}N_2O_4$ 303.1345

MS *m/z*, 303.1 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

_R_ - 3-Methyl-1-(ethylmandelylcarbonylmethyl)imidazolium bromide (213a)



Off-white powder

The title compound was prepared from *R* – ethyl mandelyl bromoacetate (20.0 mmol, 6.02 g) and 1-methylimidazole (18.0 mmol, 1.48 g) according to the general procedure in 81 % yield (5.55 g, 14.5 mmol)

Molecular formula $C_{15}H_{17}BrN_2O_4$

Molecular weight 383 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.34 (s, 1H), 7.42 (t, *J* = 1.2 Hz, 1H), 7.38-7.31 (m, 5H), 7.23 (t, *J* = 1.2 Hz, 1H), 5.91 (s, 1H), 5.74 (d, *J* = 18 Hz, 1H), 5.43 (d, *J* = 18 Hz, 1H), 4.21-4.07 (m, 2H), 3.99 (s, 3H), 1.70 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.01, 165.74, 138.71, 132.38, 129.79, 129.01, 127.83, 123.66, 122.93, 76.36, 62.30, 50.27, 36.97, 13.99

MP (°C) 130 – 132

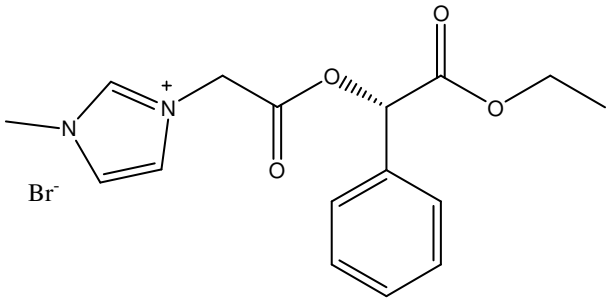
IR (KBr disc) (cm^{-1}) 2962, 2927, 2860, 1750, 1559, 1539, 1495, 1452, 1453, 1398, 1208, 1178

MS m/z, Found 303.1331 [M-Br-]$^+$, Calcd. $C_{16}H_{19}N_2O_4$ 303.1345

MS *m/z*, 303.1 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

$[\alpha]_D^{20}$ -83.8º (1.0 c, $CHCl_3$)

_S_ - 3-Methyl-1-(ethylmandelylcarbonylmethyl)imidazolium bromide (213b)



Beige powder

The title compound was prepared from *S* – ethyl mandelyl bromoacetate (24.0 mmol, 7.22 g) and 1-methylimidazole (21.0 mmol, 1.72 g) according to the general procedure in 82 % yield (6.59 g, 17.2 mmol)

Molecular formula $C_{15}H_{17}BrN_2O_4$

Molecular weight 383 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.07 (s, 1H), 7.51 (t, *J* = 1.8 Hz, 1H), 7.39-7.31 (m, 6H), 5.90 (s, 1H), 5.70 (s, 1H), 5.46 (s, 1H), 4.19-4.11 (m, 2H), 3.97 (s, 3H), 1.15 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.99, 165.75, 138.53, 132.40, 129.78, 129.01, 127.82, 123.68, 123.05, 76.34, 62.28, 50.22, 36.95, 13.99

MP (°C) 129 – 131

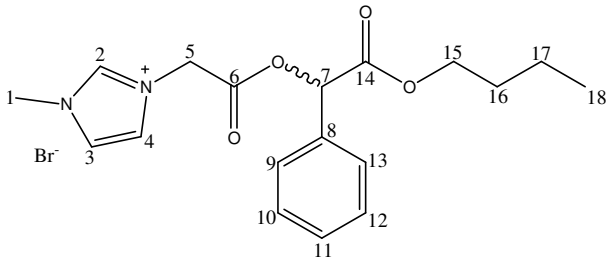
IR (KBr disc) (cm^{-1}) 2962, 2926, 2862, 1751, 1559, 159, 1495, 1452, 1398, 1209, 1175

MS m/z, Found 303.1323 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{16}H_{19}N_2O_4$ 303.1345

MS *m/z*, 303.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$: +83.4º (0.9 c, $CHCl_3$)

_RS_ - 3-Methyl-1-(butylmandelylcarbonylmethyl)imidazolium bromide (213f)



Beige powder

The title compound was prepared from *RS* – butyl mandelyl bromoacetate (22.0 mmol, 7.24 g) and 1-methylimidazole (20.0 mmol, 1.64 g) according to the general procedure in 58 % yield (4.81 g, 11.7 mmol)

Molecular formula $C_{18}H_{23}BrN_2O_4$

Molecular weight 411 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.03 (s, 1H, *H2*), 7.51 (s, 1H, *H4*), 7.40 (s, 1H, *H3*), 7.33-7.26 (m, 5H, *H's 9-13*), 5.91 (s, 1H, *H7*), 5.71 (d, *J* =18 Hz, 1H, *H5*), 5.45 (d, *J* =18 Hz, 1H, *H5*), 4.06-3.99 (m, 2H, *H15*), 3.97 (s, 3H, *H1*), 1.47-1.40 (m, 2H, *H16*), 1.61 (tq, *J* =7.4 Hz, 7.4 Hz, 2H, *H17*), 0.76 (t, *J* =7.4 Hz, 3H, *H18*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.08 (*C*O), 165.74 (*C*O), 138.48 (N*C*H_2N), 135.00 (Ar*C*), 132.47 (Ar*C*), 129.75 (Ar*C*), 125.00 (Ar*C*), 123.67 (N*C*H_2), 123.08 (N*C*H_2), 76.29 (O*C*H), 66.01 (N*C*H_2), 50.22 (O*C*H_2), 36.94 (N*C*H_3), 30.29 (*C*H_2), 18.79 (*C*H_2), 13.54 (*C*H_3)

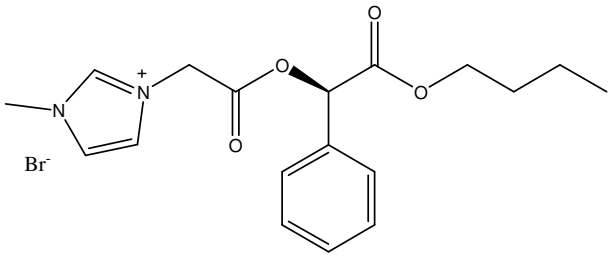
MP (°C) 118 – 120

IR (KBr disc) (cm^{-1}) 2927, 2857, 1752, 1733, 1568, 1492, 1452, 1402, 1261, 1167, 1084, 1051, 1029

MS m/z, Found 331.1646 [M-Br-]$^+$, Calcd. $C_{18}H_{23}N_2O_4$ 331.1658

MS *m/z*, 331.2 [M-Br^-]$^+$; MS: *m/z*, 79 and 81 [Br^-]

_R_ - 3-Methyl-1-(butylmandelylcarbonylmethyl)imidazolium bromide (213d)



Off-white powder

The title compound was prepared from *R* – butyl mandelyl bromoacetate (25.0 mmol, 8.23 g) and 1-methylimidazole (23.0 mmol, 1.89 g) according to the general procedure in 82 % yield (7.73 g, 18.8 mmol)

Molecular formula $C_{18}H_{23}BrN_2O_4$

Molecular weight 411 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.18 (s, 1H), 7.49 (t, *J* =1.6 Hz, 1H), 7.34-7.26 (m, 6H), 5.91 (s, 1H), 5.75 (d, *J* =17.8 Hz, 1H), 5.43 (d, *J* =17.8 Hz, 1H), 4.06-4.02 (m, 2H), 3.98 (s, 3H), 1.46-1.43 (m, 2H), 1.67 (tq, *J* =7.4 Hz, 7.5 Hz, 2H), 0.77 (t, *J* = 7.5 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.04, 165.66, 138.65, 132.42, 129.77, 128.99, 127.77, 123.66, 122.98, 76.34, 66.02, 50.24, 36.95, 30.31, 18.81, 13.56

MP (°C) 88 – 90

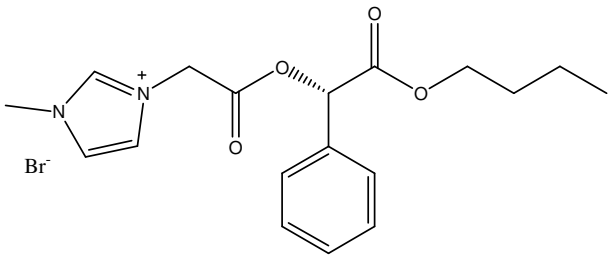
IR (KBr disc) (cm^{-1}) 2930, 2859, 1751, 1730, 1561, 1497, 1445, 1400, 1261, 1166, 1079, 1050, 1028

MS m/z, Found 331.1667 [M-Br-]$^+$, Calcd. $C_{18}H_{23}N_2O_4$ 331.1658

MS *m/z*, 331.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$ -74.7º (0.9 c, $CHCl_3$)

S - 3-Methyl-1-(butylmandelylcarbonylmethyl)imidazolium bromide (213h)



White powder

The title compound was prepared from *S* – butyl mandelyl bromoacetate (15.0 mmol, 4.94 g) and 1-methylimidazole (13.0 mmol, 1.07 g) according to the general procedure in 64 % yield (3.43 g, 8.35 mmol)

Molecular formula $C_{18}H_{23}BrN_2O_4$

Molecular weight 411 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.11 (s, 1H), 7.52 (t, *J* = 1.8 Hz, 1H), 7.45 (t, *J* = 1.8 Hz, 1H), 7.34-7.28 (m, 5H), 5.91 (s, 1H), 5.73 (d, *J* = 18 Hz, 1H), 7.45 (d, *J* = 18 Hz, 1H), 4.06-3.97 (m, 2H), 3.97 (s, 3H), 1.46-1.40 (m, 2H), 1.62 (tq, *J* = 7.4 Hz, 7.4 Hz, 2H), 0.77 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.02, 165.69, 138.46, 132.46, 129.75, 128.98, 127.76, 123.68, 123.13, 76.31, 66.00, 50.19, 36.93, 30.29, 18.80, 13.55

MP (°C) 89 – 91

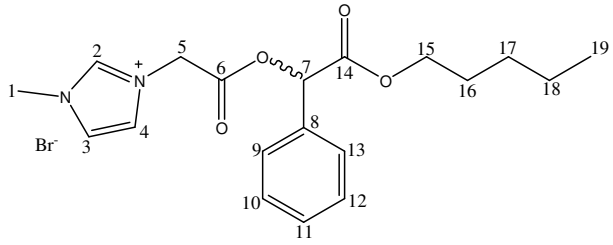
IR (KBr disc) (cm^{-1}) 2932, 2863, 1751, 1730, 1572, 1496, 1451, 1401, 1255, 1162, 1089, 1051, 1029

MS m/z, Found 331.1647 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{18}H_{23}N_2O_4$ 331.1658

MS *m/z*, 331.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$ +77.7º (0.9 c, $CHCl_3$)

***RS* - 3-Methyl-1-(pentylmandelylcarbonylmethyl)imidazolium bromide (213i)**



Off-white powder

The title compound was prepared from *RS* – pentyl mandelyl bromoacetate (20.0 mmol, 6.86 g) and 1-methylimidazole (18.0 mmol, 1.48 g) according to the general procedure in 60 % yield (4.59 g, 10.8 mmol)

Molecular formula $C_{19}H_{25}BrN_2O_4$

Molecular weight 425 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.17 (s, 1H, *H2*), 7.50 (t, *J* = 1.8 Hz, 1H, *H4*), 7.34-7.25 (m, 6H, *H's 4 and 9-13*), 5.91 (s, 1H, *H7*), 5.72 (d, *J* = 18 Hz, 1H, *H5*), 5.44 (d, *J* = 18 Hz, 1H, *H5*), 5.04-4.97 (m, 2H, *H15*), 3.97 (s, 3H, *H1*), 1.48 (tt, *J* = 6.8, 7.4 Hz, 2H, *H16*), 1.10-0.99 (m, 4H, *H's 17 and 18*), 0.75 (t, *J* = 7.4 Hz, 3H, *H19*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.08 (*C*O), 165.71 (*C*O), 138.60 (N*C*H$_2$N), 132.47 (Ar*C*), 129.75 (Ar*C*), 127.00 (Ar*C*), 123.65 (Ar*C*), 122.99 (N*C*H$_2$), 122.04 (N*C*H$_2$), 76.29 (O*C*H), 66.26 (N*C*H$_2$), 50.24 (*C*O), 36.94 (N*C*H$_3$), 27.98 (*C*H$_2$), 27.65 (*C*H$_2$), 22.10 (*C*H$_2$), 13.88 (*C*H$_3$)

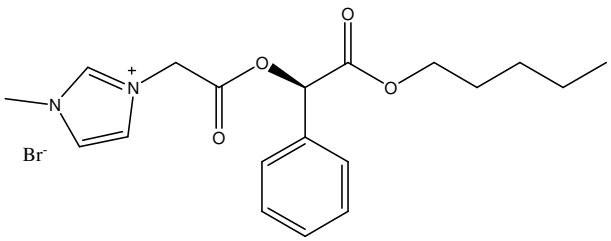
MP (°C) 127 – 129

IR (KBr disc) (cm^{-1}) 2959, 2926, 2859, 1751, 1608, 1559, 1539, 1495, 1452, 1403, 1210, 1176

MS m/z, Found 345.1812 [M-Br-]$^+$, Calcd. $C_{19}H_{25}N_2O_4$ 345.1814

MS *m/z*, 345.2 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

***R* - 3-Methyl-1-(pentylmandelylcarbonylmethyl)imidazolium bromide (213g)**



Brown powder

The title compound was prepared from *R* – pentyl mandelyl bromoacetate (26.0 mmol, 8.92 g) and 1-methylimidazole (22.0 mmol, 1.80 g) according to the general procedure in 68 % yield (6.38 g, 15.0 mmol)

Molecular formula $C_{19}H_{25}BrN_2O_4$

Molecular weight 425 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.07 (s, 1H), 7.59 (t, *J* = 1.8 Hz, 1H), 7.48 (t, *J* = 1.8 Hz, 1H), 7.45-7.39 (m, 5H), 5.99 (s, 1H), 5.78 (d, *J* = 18 Hz, 1H), 5.53 (d, *J* = 18 Hz, 1H), 4.11 (t, *J* = 6.8 Hz, 2H), 4.05 (s, 1H), 1.59 (tt, *J* = 6.8, 7.0 Hz, 2H), 1.26-1.11 (m, 4H), 0.82 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.09, 165.75, 138.49, 132.50, 129.74, 128.97, 127.77, 123.68, 123.08, 76.28, 66.26, 50.24, 36.95, 27.98, 27.64, 22.09, 13.88

MP (°C) 44 – 45

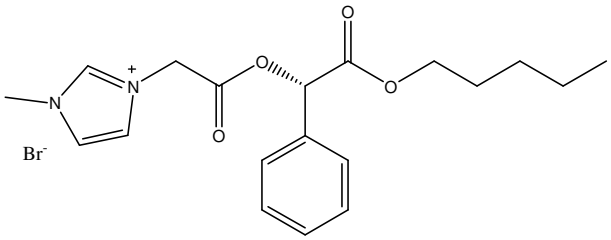
IR (KBr disc) (cm^{-1}) 2959, 2928, 2859, 1733, 1608, 1559, 1539, 1495, 1452, 1398, 1207, 1179

MS m/z, Found 345.1818 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{19}H_{25}N_2O_4$ 345.1814

MS *m/z*, 345.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$ -71.3º (0.8 c, $CHCl_3$)

_S_ - 3-Methyl-1-(pentylmandelylcarbonylmethyl)imidazolium bromide (213h)



Pale brown powder

The title compound was prepared from *S* – pentyl mandelyl bromoacetate (24.0 mmol, 8.23 g) and 1-methylimidazole (20.0 mmol, 1.64 g) according to the general procedure in 73 % yield (6.21 g, 14.6 mmol)

Molecular formula $C_{19}H_{25}BrN_2O_4$

Molecular weight 425 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.13 (s, 1H), 7.47 (s, 1H), 7.37-7.29 (m, 6H), 5.91 (s, 1H), 5.73 (d, *J* = 18 Hz, 1H), 5.43 (d, *J* = 18 Hz, 1H), 4.06 (t, *J* = 7.4 Hz, 2H), 3.98 (s, 3H), 1.50 (tt, *J* = 7.4, 7.4 Hz, 2H), 1.12-1.01 (m, 4H), 0.75 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.11, 165.83, 138.21, 132.54, 129.71, 128.95, 127.76, 123.69, 123.28, 76.21, 66.22, 50.20, 36.94, 27.95, 27.62, 22.07, 13.87

MP (°C) 73 – 75

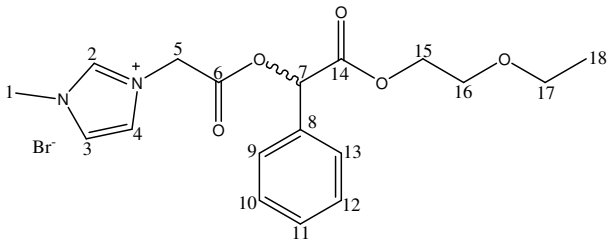
IR (KBr disc) (cm^{-1}) 2958, 2928, 2859, 1750, 1559, 1539, 1495, 1456, 1206, 1174

MS m/z, Found 345.1808 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{19}H_{25}N_2O_4$ 345.1814

MS *m/z*, 345.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$ +72.0º (0.8 c, $CHCl_3$)

***RS* - 3-Methyl-1-(ethoxyethylmandelylcarbonylmethyl)imidazolium bromide (213l)**



Off-white powder

The title compound was prepared from *RS* – ethoxy ethyl mandelyl bromoacetate (34.0 mmol, 11.73 g) and 1-methylimidazole (31.0 mmol, 2.54 g) according to the general procedure in 76 % yield (9.99 g, 23.4 mmol)

Molecular formula $C_{18}H_{23}BrN_2O_5$

Molecular weight 427 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.96 (s, 1H, *H2*), 7.60 (t, *J* = 1.8 Hz, 1H, *H4*), 7.52 (t, *J* = 1.8 Hz, 1H, *H3*), 7.34-7.27 (m, 5H, *H's 9-13*), 5.95 (s, 1H, *H7*), 5.70 (d, *J* = 17.8 Hz, 1H, *H5*), 5.48 (d, *J* = 17.8 Hz, 1H, *H5*), 4.21 (t, *J* = 4.6 Hz, 2H, *H15*), 3.97 (s, 3H, *H1*), 3.48 (t, *J* = 4.6 Hz, 2H, *H16*), 3.31 (q, *J* = 7.0 Hz, 2H, *H17*), 1.02 (t, *J* = 7.0 Hz, 3H, *H18*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.91 (*C*O), 166.27 (*C*O), 138.20 (N*C*H$_2$N), 132.29 (Ar*C*), 129.75 (Ar*C*), 128.94 (Ar*C*), 127.83 (Ar*C*), 123.77 (N*C*H$_2$), 123.32 (N*C*H$_2$), 76.18 (O*C*H), 67.80 (N*C*H$_2$), 66.65 (N*C*H$_2$), 65.75 (O*C*H$_2$), 50.15 (O*C*H$_2$), 36.86 (O*C*H$_2$), 15.04 (*C*H$_3$)

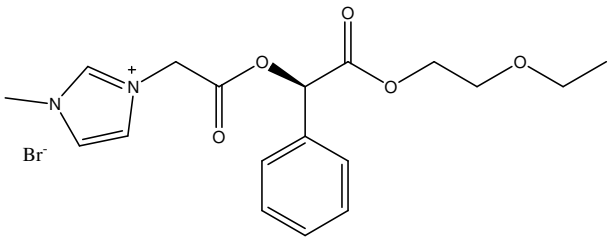
MP (°C) 124 – 126

IR (KBr disc) (cm^{-1}) 2969, 2925, 2861, 1733, 1560, 1535, 1493, 1452, 1401, 1370, 1211, 1174

MS m/z, Found 347.1611 [M-Br-]$^+$, Calcd. $C_{18}H_{23}N_2O_5$ 347.1607

MS *m/z*, 347.2 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

_R_ - 3-Methyl-1-(ethoxyethylmandelylcarbonylmethyl)imidazolium bromide (213j)



Brown solid

The title compound was prepared from *R* – ethoxy ethyl mandelyl bromoacetate (28.0 mmol, 9.66 g) and 1-methylimidazole (22.0 mmol, 1.80 g) according to the general procedure in 71 % yield (6.70 g, 15.7 mmol)

Molecular formula $C_{18}H_{23}BrN_2O_5$

Molecular weight 427 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.10 (s, 1H), 7.64 (t, *J* = 1.6 Hz, 1H), 7.57 (t, *J* = 1.6 Hz, 1H), 7.39-7.30 (m, 5H), 5.99 (s, 1H), 5.74 (d, *J* = 17.8 Hz, 1H), 7.52 (d, *J* = 17.8 Hz, 1H), 4.26 (t, *J* = 5.0 Hz, 2H), 4.00 (s, 3H), 3.52 (t, *J* = 5.0 Hz, 2H), 3.39 (q, *J* = 7.2 Hz, 2H), 1.07 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.97, 165.80, 138.35, 132.30, 129.77, 128.95, 127.86, 123.75, 123.19, 76.20, 67.82, 66.54, 65.09, 50.17, 36.92, 15.04

MP (°C) 31 – 33

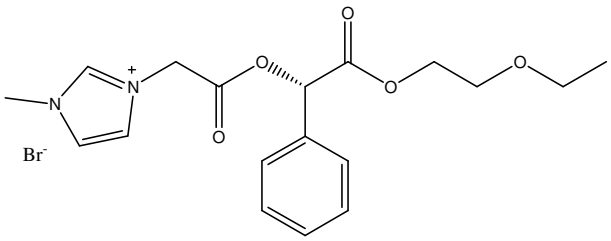
IR (KBr disc) (cm^{-1}) 2968, 2927, 2862, 1733, 1559, 1539, 1495, 1452, 1402, 1375, 1215, 1176

MS m/z, Found 347.1593 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{18}H_{23}N_2O_5$ 347.1607

MS *m/z*, 347.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$ -66.2° (1.1 c, $CHCl_3$)

_S_ - 3-Methyl-1-(ethoxyethylmandelylcarbonylmethyl)imidazolium bromide (213k)



Brown viscous liquid

The title compound was prepared from *S* – ethoxy ethyl mandelyl bromoacetate (8.00 mmol, 2.76 g) and 1-methylimidazole (6.00 mmol, 0.49 g) according to the general procedure in 85 % yield (2.17 g, 5.08 mmol)

Molecular formula $C_{18}H_{23}BrN_2O_5$

Molecular weight 427 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.10 (s, 1H), 7.63 (t, *J* = 1.8 Hz, 1H), 7.58 (t, *J* = 1.8 Hz, 1H), 7.38-7.29 (m, 5H), 5.95 (s, 1H), 5.73 (d, *J* = 18 Hz, 1H), 5.54 (d, *J* = 18 Hz, 1H), 4.15-4.08 (m, 2H), 4.01 (s, 3H), 3.53-3.50 (m, 2H), 3.22-3.15 (m, 2H), 1.19 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.94, 165.78, 138.22, 132.44, 129.75, 128.99, 127.78, 123.73, 123.30, 76.29, 67.80, 66.66, 62.24, 50.15, 36.91, 13.98

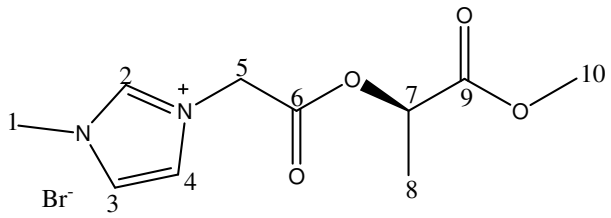
IR (thin film on salt plate) (cm^{-1}) 2969, 2926, 1751, 1608, 1559, 1539, 1495, 1452, 1378, 1211, 1176

MS m/z, Found 347.1599 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{18}H_{23}N_2O_5$ 347.1607

MS *m/z*, 347.2 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$ +65.6º (1.1 c, $CHCl_3$)

_R_ - 3-Methyl-1-(methyllactylcarbonylmethyl)imidazolium bromide (214a)



Off-white powder

The title compound was prepared from *R* – methyl lactyl bromoacetate (14.0 mmol, 3.15 g) and 1-methylimidazole (13.0 mmol, 1.07 g) according to the general procedure in 66 % yield (2.61 g, 8.52 mmol)

Molecular formula $C_{10}H_{15}BrN_2O_4$

Molecular weight 307 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.07 (s, 1H, *H2*), 7.70 (t, *J* = 1.8 Hz, 1H, *H4*), 7.64 (t, *J* = 1.8 Hz, 1H, *H3*), 5.72 (d, *J* = 18 Hz, 1H, *H5*), 5.47 (d, *J* = 18 Hz, 1H, *H*5), 5.16 (q, *J* = 7.2 Hz, 1H, *H7*), 4.07 (s, 3H, *H1*), 3.72 (s, 3H, *H10*), 1.52 (d, *J* = 7.2 Hz, 3H, *H8*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 170.25 (*C*O), 165.73 (*C*O), 138.17 (N*C*H_2N), 123.84 (N*C*H_2), 123.32 (N*C*H_2), 70.64 (*C*H), 52.78 (N*C*H_2), 50.09 (O*C*H_3), 36.95 (N*C*H_3), 16.84 (*C*H_3)

MP (°C) 115 – 117

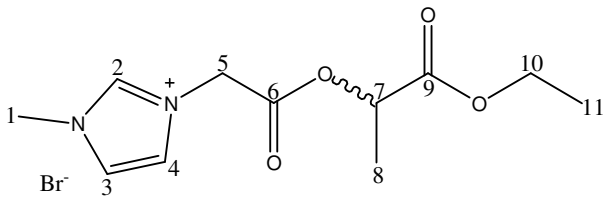
IR (KBr disc) (cm^{-1}) 2928, 2863, 1751, 1632, 1569, 1559, 1495, 1451, 1377, 1217, 1178

MS m/z, Found 227.1032 [M-Br-]$^+$, Calcd. $C_{10}H_{15}N_2O_4$ 227.1032

MS *m/z*, 227.1 [M-Br^-]$^+$; MS: *m/z*, 79 and 81 [Br^-]

$[\alpha]_D^{20}$ -37.3º (0.4 c, $CHCl_3$)

_RS_ - 3-Methyl-1-(ethyllactylcarbonylmethyl)imidazolium bromide (214d)



Yellow viscous liquid

The title compound was prepared from *RS* – ethyl lactyl bromoacetate (98.0 mmol, 23.42 g) and 1-methylimidazole (89.0 mmol, 7.30 g) according to the general procedure in 88 % yield (25.30 g, 78.8 mmol)

Molecular formula $C_{11}H_{17}BrN_2O_4$

Molecular weight 321 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.02 (s, 1H, *H2*), 7.62 (t, *J* = 1.8 Hz, 1H, *H4*), 7.56 (t, *J* = 1.8 Hz, 1H, *H3*), 5.70 (d, *J* = 18.0 Hz, 1H, *H5*), 5.40 (d, *J* = 18.0 Hz, 1H, *H5*), 5.13 (q, *J* = 7.2, 1H, *H7*), 4.16 (q, *J* = 7.2, 2H, *H10*), 4.06 (s, 3H, *H1*), 1.49 (d, *J* = 7.2 Hz, 3H, *H8*), 1.23 (t, *J* = 7.2 Hz, 3H, *H11*)

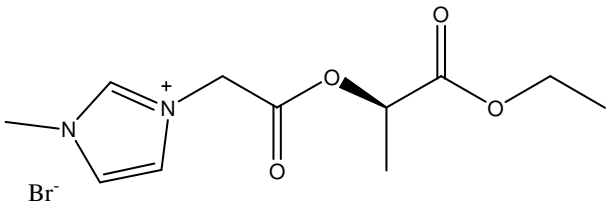
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.92 (*C*O), 165.83 (*C*O), 138.23 (N*C*H$_2$N), 123.78 (N*C*H$_2$), 123.30 (N*C*H$_2$), 70.72 (*C*H), 61.92 (N*C*H$_2$), 50.17 (O*C*H$_2$), 37.01 (N*C*H$_3$), 16.84 (*C*H$_3$), 14.12 (*C*H$_3$)

IR (thin film on salt plate) (cm^{-1}) 3163, 3099, 2929, 2858, 1748, 1636, 1559, 1495, 1451, 1397, 1374, 1209, 1177

MS m/z, Found 241.1178 [M-Br-]$^+$, Calcd. $C_{11}H_{17}N_2O_4$ 241.1188

MS *m/z*, 241.1 [M-Br$^-$]$^+$; MS: *m/z*, 79 and 81 [Br$^-$]

_R_ - 3-Methyl-1-(ethyllactylcarbonylmethyl)imidazolium bromide (214c)



Pale brown viscous liquid

The title compound was prepared from *R* – ethyl lactyl bromoacetate (19.0 mmol, 4.54 g) and 1-methylimidazole (17.0 mmol, 1.39 g) according to the general procedure in 77 % yield (4.21 g, 13.1 mmol)

Molecular formula $C_{11}H_{17}BrN_2O_4$

Molecular weight 321 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.25 (s, 1H), 7.49 (t, *J* = 1.8 Hz, 1H), 7.35 (t, *J* = 1.8 Hz, 1H), 5.77 (d, *J* = 17.6 Hz, 1H), 5.33 (d, *J* = 17.6 Hz, 1H), 5.13 (q, *J* = 7.2 Hz, 1H), 4.17 (q, *J* = 7.0 Hz, 2H), 4.02 (s, 3H), 1.50 (d, *J* = 7.2 Hz, 3H), 1.24 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.94, 165.80, 138.25, 123.81, 123.32, 70.71, 61.92, 50.16, 37.06, 16.90, 14.17

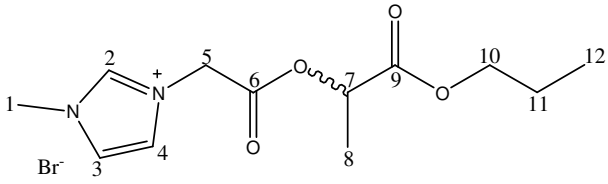
IR (thin film on salt plate) (cm^{-1}) 3159, 3099, 2926, 2858, 1748, 1566, 1559, 1495, 1451, 1209, 1177

MS m/z, Found 241.1180 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{11}H_{17}N_2O_4$ 241.1188

MS *m/z*, 241.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$ -39.1º (0.4 c, $CHCl_3$)

RS - 3-Methyl-1-(propyllactylcarbonylmethyl)imidazolium bromide (214f)



Brown viscous liquid

The title compound was prepared from *RS* – propyl lactyl bromoacetate (30.0 mmol, 7.59 g) and 1-methylimidazole (28.0 mmol, 2.30 g) according to the general procedure in 88 % yield (8.25 g, 24.6 mmol)

Molecular formula $C_{12}H_{19}BrN_2O_4$

Molecular weight 335 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.13 (s, 1H, *H2*), 7.55 (t, *J* = 1.8 Hz, 1H, *H4*), 7.47 (t, *J* = 1.8 Hz, 1H, *H3*), 5.74 (d, *J* = 17.6 Hz, 1H, *H5*), 5.35 (d, *J* = 17.6 Hz, 1H, *H5*), 5.14 (q, *J* = 7.2 Hz, 1H, *H7*), 4.06-4.01 (m, 3H, *H1*), 3.89 (t, *J* = 7.2 Hz, 2H, *10H*) 1.64 (tq, *J* = 7.2, 7.2 Hz, 2H, *H11*), 1.50 (d, *J* = 7.2 Hz, 3H, *H8*), 0.89 (t, *J* = 7.2 Hz, 3H, *H12*)

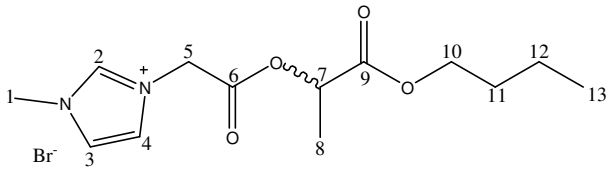
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.90 (*C*O), 165.66 (*C*O), 138.50 (N*C*H_2N), 123.71 (N*C*H_2), 123.10 (N*C*H_2), 70.78 (*C*H), 67.37 (N*C*H_2), 30.17 (O*C*H_2), 36.99 (N*C*H_3), 21.85 (*C*H_3), 16.87 (*C*H_2), 10.27 (*C*H_3)

IR (thin film on salt plate) (cm^{-1}) 3099, 2968, 2927, 2859, 1751, 1559, 1495, 1452, 1397, 1372, 1205, 1177

MS m/z, Found 255.1337 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{12}H_{19}N_2O_4$ 255.1345

MS *m/z*, 255.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

_RS_ - 3-Methyl-1-(butyllactylcarbonylmethyl)imidazolium bromide (214h)



Pale brown viscous liquid

The title compound was prepared from *RS* – butyl lactyl bromoacetate (32.2 mmol, 8.60 g) and 1-methylimidazole (30.0 mmol, 2.46 g) according to the general procedure in 82 % yield (8.61 g, 24.7 mmol)

Molecular formula $C_{13}H_{21}BrN_2O_4$

Molecular weight 349 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.13 (s, 1H, *H2*), 7.58 (t, *J* = 1.8 Hz, 1H, *H4*), 7.49 (t, *J* = 1.8 Hz, 1H, *H3*), 5.66 (d, *J* = 17.6 Hz, 1H, *H5*), 5.31 (d, *J* = 17.6 Hz, 1H, *H5*), 5.14 (q, *J* = 7.2 Hz, 1H, *H7*), 4.14 (m, 2H, *H10*), 4.02 (s, 3H, *H1*), 1.60 (tt, *J* = 7.2, 7.4 Hz, 2H, *H11*), 1.50 (d, *J* = 7.2 Hz, 3H, *H8*), 1.36 (tq, J= 7.4 , 7.4 Hz, 2H, *H12*), 0.88 (t, *J* = 7.4 Hz, 3H, *H13*)

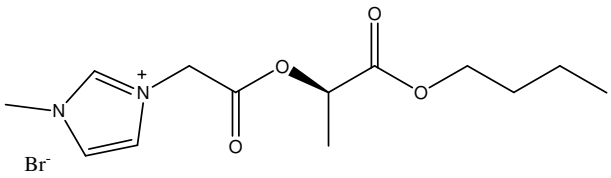
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.97 (*C*O), 165.77 (*C*O), 138.30 (N*C*H$_2$N), 123.74 (N*C*H$_2$), 123.26 (N*C*H$_2$), 70.70 (*C*H), 65.69 (N*C*H$_2$), 50.18 (O*C*H$_2$), 37.42 (N*C*H$_3$), 30.42 (*C*H$_3$), 18.96 (*C*H$_2$), 16.88 (*C*H$_2$), 13.65 (*C*H$_3$)

IR (thin film on salt plate) (cm^{-1}) 3158, 3095, 2962, 2928, 2862, 1751, 1569, 1559, 1495, 1457, 1202, 1178

MS m/z, Found 269.1499 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{13}H_{21}N_2O_4$ 269.1501

MS *m/z*, 269.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

***R* - 3-Methyl-1-(butyllactylcarbonylmethyl)imidazolium bromide (214g)**



Pale brown viscous liquid

The title compound was prepared from *R* – butyl lactyl bromoacetate (37.0 mmol, 9.88 g) and 1-methylimidazole (33.0 mmol, 2.71 g) according to the general procedure in 86 % yield (9.88 g, 28.3 mmol)

Molecular formula $C_{13}H_{21}BrN_2O_4$

Molecular weight 349 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 10.08 (s, 1H), 7.55 (t, *J* = 1.8 Hz, 1H), 7.46 (t, *J* = 1.8 Hz, 1H), 5.74 (d, *J* = 17.6 Hz, 1H), 5.35 (d, *J* = 17.6 Hz, 1H), 5.14 (q, *J* = 7.2 Hz, 1H), 4.10 (m, 2H), 4.03 (s, 3H), 1.60 (tt, *J* = 7.2, 7.3 Hz, 2H), 1.50 (d, *J* = 7.2 Hz, 3H), 1.33 (tq, *J* = 7.3, 7.4 Hz, 2H), 0.88 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 170.01, 165.79, 138.29, 123.75, 123.27, 70.68, 65.66, 50.18, 37.41, 30.42, 18.98, 16.89, 13.64

IR (thin film on salt plate) (cm^{-1}) 3154, 3099, 2962, 2928, 2863, 1751, 1634, 1580, 1559, 1495, 1457, 1399, 1204, 1175

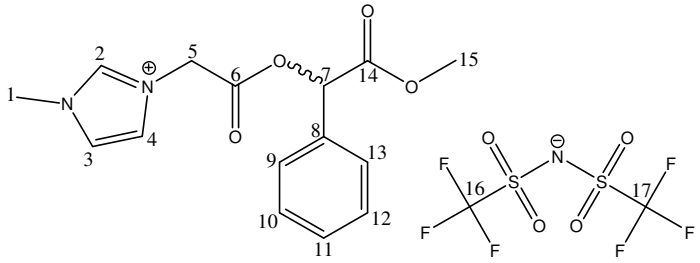
MS m/z, Found 269.1492 $[M\text{-}Br\text{-}]^+$, Calcd. $C_{13}H_{21}N_2O_4$ 269.1501

MS *m/z*, 269.1 $[M\text{-}Br^-]^+$; MS: *m/z*, 79 and 81 $[Br^-]$

$[\alpha]_D^{20}$ -34.0º (0.5 c, $CHCl_3$)

Chiral NTf_2 salts

Representative procedure for the preparation of chiral NTf_2 salts (*RS* - 3-methyl-1-(methylmandelylcarbonylmethyl)imidazolium NTf_2) (215o)



A flask was charged with *RS*-3-methyl-1-(methyl mandelyl carbonylmethyl) imidazolium bromide **213o** (0.67 g, 1.81 mmol) and distilled water (10 mL). $LiNTf_2$ (0.86 g, 3.00 mmol) was added in one portion and the suspension was stirred vigorously for overnight at RT. The top aqueous layer was removed and the IL was washed with distilled water (3 x 5 mL). The solvent was then removed on the rotary evaporator and under high vacuum for 5 h to give an orange crystalline material at RT in 92 % yield (0.95 g, 1.67 mmol)

Molecular formula $C_{17}H_{18}F_6N_3O_8S_2$

Molecular weight 569 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.73 (s, 1H, *H1*), 7.32 (s, 5H, *H's 9-13*), 7.31 (s, 1H, *H4*), 7.22 (s, 1H, *H3*), 5.93 (s, 1H, *H7*), 5.08 (s, 2H, *H5*), 3.84 (s, 3H, *H1*), 3.62 (s, 3H, *H15*)

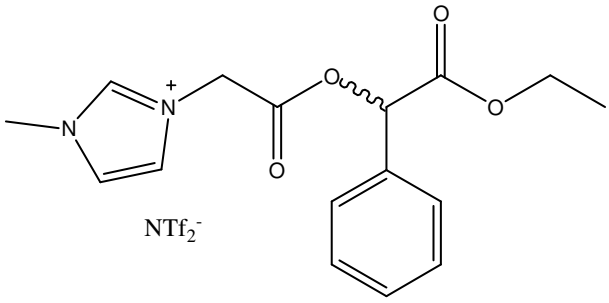
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.42 (*C*OO), 165.33 (*C*OO), 137.68 (Ar*C*), 132.25 (N*C*HN), 129.91 (Ar*C* x 2), 129.05 (Ar*C* x 2), 127.79 (Ar*C*), 123.77 (N*C*H), 123.21 (N*C*H), 121.00 (q, J = 319 Hz, 2*C*F_3), 76.36 (O*C*H), 63.34 (N*C*H_2), 49.80 (O*C*H_3), 36.56 (N*C*H_3)

MP (°C) 73 – 75

IR (KBr disc) (cm^{-1}) 3470, 3379, 2099, 1750, 1571, 1566, 1459, 1453, 1451, 1390, 1197, 1127

MS *m/z*, 289.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

***RS* - 3-Methyl-1-(ethylmandelylcarbonylmethyl)imidazolium NTf_2 (215c)**



Pale brown viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(ethyl mandelyl carbonyl methyl) imidazolium bromide **213c** (0.96 g, 2.60 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 95 % yield (1.43 g, 2.45 mmol)

Molecular formula $C_{18}H_{20}F_6N_3O_8S_2$

Molecular weight 583 g/mol

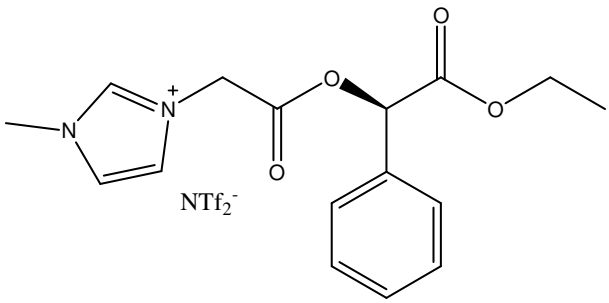
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.79 (s, 1H), 7.37 – 7.35 (m, 5H), 7.31 (t, *J* = 1.8 Hz, 1H), 7.22 (t, *J* = 1.8 Hz, 1H), 5.91 (s, 1H), 5.10 (d, *J* = 2.8 Hz, 2H), 4.20 – 4.03 (m, 2H), 3.87 (s, 3H), 1.13 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.89, 165.27, 137.84, 132.29, 129.86, 129.02, 127.78, 123.71, 123.25, 121.27 (q, J = 320 Hz, 2*C*F_3), 76.52, 62.33, 49.88, 36.64, 13.91

IR (thin film on salt plate) (cm^{-1}) 3167, 3120, 2960, 2927, 2860, 1751, 1566, 1559, 1540, 1495, 1457, 1354, 1198, 1136

MS *m/z*, 303.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

***R* - 3-Methyl-1-(ethylmandelylcarbonylmethyl)imidazolium NTf_2 (215a)**



Orange solid

The title compound was prepared from *R* - 3-methyl-1-(ethyl mandelyl carbonyl methyl) imidazolium bromide **213a** (1.03 g, 2.70 mmol) and $LiNTf_2$ (0.86 g, 3.00 mmol) according to the general procedure in 95 % yield (1.41 g, 2.41 mmol)

Molecular formula $C_{18}H_{20}F_6N_3O_8S_2$

Molecular weight 583 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.67 (s, 1H), 7.36 – 7.29 (m, 6H), 7.24 (t, *J* = 1.6 Hz, 1H), 5.88 (s, 1H), 5.05 (s, 2H), 4.16-4.11 (m, 2H), 3.81 (s, 3H), 1.10 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.92, 165.38, 137.49, 132.40, 129.81, 128.99, 127.74, 123.74, 123.46, 121.58 (q, *J* = 320 Hz, 2*C*F_3), 76.46, 62.29, 49.72, 36.47, 13.84

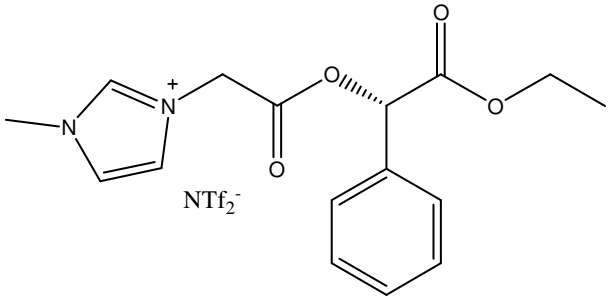
MP (°C) 44 – 46

IR (KBr disc) (cm^{-1}) 3156, 3099, 3007, 1761, 1735, 1579, 1568, 1500, 1456, 1430, 1371, 1356, 1279, 1187, 1132, 1051

MS *m/z*, 303.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -53.7º (0.5 c, $CHCl_3$)

S - 3-Methyl-1-(ethylmandelylcarbonylmethyl)imidazolium NTf_2 (215b)



Amber solid

The title compound was prepared from *S* - 3-methyl-1-(ethyl mandelyl carbonyl methyl) imidazolium bromide **213b** (0.96 g, 2.50 mmol) and $LiNTf_2$ (0.86 g, 3.00 mmol) according to the general procedure in 85 % yield (1.42 g, 2.44 mmol)

Molecular formula $C_{18}H_{20}F_6N_3O_8S_2$

Molecular weight 583 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.72 (s, 1H), 7.36 – 7.32 (m, 5H), 7.30 (t, *J* = 1.8 Hz, 1H), 7.23 (t, *J* = 1.8 Hz, 1H), 5.89 (s, 1H), 5.07 (s, 2H), 4.18 – 4.02 (m, 2H), 3.85 (s, 3H), 1.12 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.92, 165.34, 137.64, 132.36, 129.83, 129.01, 127.76, 123.74, 123.38, 121.44 (q, *J* = 320 Hz, 2*C*F_3), 76.49, 62.31, 49.80, 36.55, 13.88

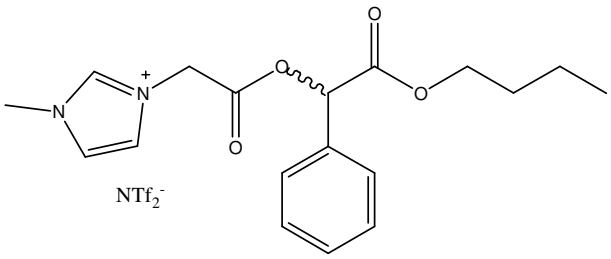
MP (°C) 44 – 46

IR (KBr disc) (cm^{-1}) 3165, 3099, 2998, 2963, 1759, 1735, 1579, 1564, 1496, 1452, 1434, 1356, 1279, 1198, 1134, 1044

MS *m/z*, 303.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ +54.7º (0.7 c, $CHCl_3$)

RS - 3-Methyl-1-(butylmandelylcarbonylmethyl)imidazolium NTf_2 (215f)



Brown viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(butyl mandelyl carbonyl methyl) imidazolium bromide **213f** (1.03 g, 2.50 mmol) and $LiNTf_2$ (0.86 g, 3.00 mmol) according to the general procedure in 94 % yield (1.45 g, 2.36 mmol)

Molecular formula $C_{20}H_{24}F_6N_3O_8S_2$

Molecular weight 612 g/mol

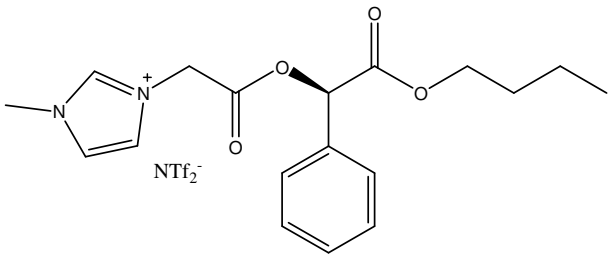
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.86 (s, 1H), 7.49 – 7.40 (m, 5H), 7.40 (t, *J* = 1.4 Hz, 1H), 7.31 (t, *J* = 1.4 Hz, 1H), 6.00 (s, 1H), 5.18 (d, *J* = 4.8 Hz, 2H), 4.20 – 4.09 (m, 2H), 3.95 (s, 3H), 1.59 – 1.52 (m, 2H), 1.25 (tq, *J* = 7.4, 7.5 Hz, 2H), 0.85 (t, *J* = 7.5 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.99, 165.26, 137.79, 132.35, 129.83, 129.0, 127.73, 123.72, 123.29, 121.20 (q, *J* = 319 Hz, 2*C*F_3), 76.49, 66.07, 49.87, 36.63, 30.28, 18.78, 13.51

IR (thin film on salt plate) (cm^{-1}) 3163, 3120, 2963, 2931, 2860, 1751, 1569, 1559, 1540, 1495, 1457, 1354, 1198, 1136

MS *m/z*, 331.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

R - 3-Methyl-1-(butylmandelylcarbonylmethyl)imidazolium NTf_2 (215d)



Orange viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(butyl mandelyl carbonyl methyl) imidazolium bromide **213d** (1.23 g, 3.00 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 98 % yield (1.80 g, 2.93 mmol)

Molecular formula $C_{20}H_{24}F_6N_3O_8S_2$

Molecular weight 612 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.81 (s, 1H), 7.45 – 7.41 (m, 5H), 7.39 (t, *J* = 1.6 Hz, 1H), 7.32 (t, *J* = 1.6 Hz, 1H), 5.99 (s, 1H), 5.16 (d, *J* = 3.2 Hz, 2H), 4.18 – 4.08 (m, 2H), 3.93 (s, 3H), 1.59 – 1.51 (m, 2H), 1.24 (tq, *J* = 7.4, 7.5 Hz, 2H), 0.85 (t, *J* =7.5 Hz, 3H)

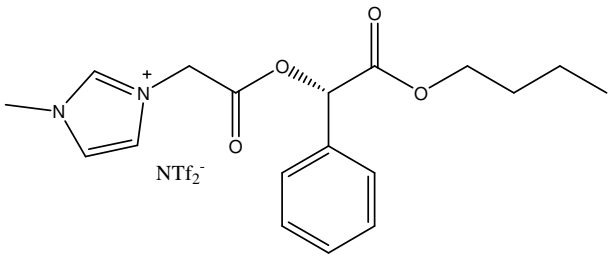
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.98, 165.30, 137.65, 132.39, 129.81, 128.98, 127.72, 123.72, 123.37, 121.26 (q, *J* = 319 Hz, 2*C*F_3), 76.47, 66.04, 49.81, 36.56, 30.26, 18.77, 13.49

IR (thin film on salt plate) (cm^{-1}) 3162, 3124, 2963, 2928, 2860, 1751, 1569, 1559, 1540, 1495, 1457, 1353, 1198, 1136

MS *m/z*, 331.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -49.0º (1.1 c, $CHCl_3$)

S - 3-Methyl-1-(butylmandelylcarbonylmethyl)imidazolium NTf_2 (215e)



Yellow viscous liquid

The title compound was prepared from *S* - 3-methyl-1-(butyl mandelyl carbonyl methyl) imidazolium bromide **213e** (1.03 g, 2.50 mmol) and $LiNTf_2$ (0.86 g, 3.00 mmol) according to the general procedure in 93 % yield (1.42 g, 2.32 mmol)

Molecular formula $C_{20}H_{24}F_6N_3O_8S_2$

Molecular weight 612 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.74 (s, 1H), 7.36 – 7.33 (m, 5H), 7.30 (t, *J* = 1.8 Hz, 1H), 7.23 (t, *J* = 1.8 Hz, 1H), 5.90 (s, 1H), 5.08 (d, *J* = 4.4 Hz, 2H), 4.10 – 4.00 (m, 2H), 3.85 (s, 3H), 1.50 – 1.43 (m, 2H), 1.18 (tq, *J* = 7.4 Hz, 7.4 Hz, 2H), 0.77 (t, *J* = 7.4 Hz, 3H)

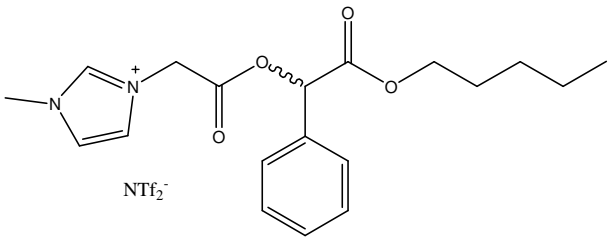
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.98, 165.28, 137.72, 129.82, 128.99, 127.73, 123.71, 123.33, 121.25 (q, *J* = 320 Hz, 2*C*F_3), 76.48, 66.05, 49.83, 36.59, 30.27, 18.78, 13.50

IR (thin film on salt plate) (cm^{-1}) 3165, 3123, 2963, 2928, 1751, 1566, 1559, 1539, 1495, 1457, 1354, 1198, 1136

MS *m/z*, 331.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ +50.4º (0.5 c, $CHCl_3$)

RS - 3-Methyl-1-(pentylmandelylcarbonylmethyl)imidazolium NTf_2 (215i)



Brown viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(pentyl mandelyl carbonyl methyl) imidazolium bromide **213i** (1.06 g, 2.50 mmol) and $LiNTf_2$ (0.86 g, 3.00 mmol) according to the general procedure in 93 % yield (1.45 g, 2.32 mmol)

Molecular formula $C_{21}H_{26}F_6N_3O_8S_2$

Molecular weight 625 g/mol

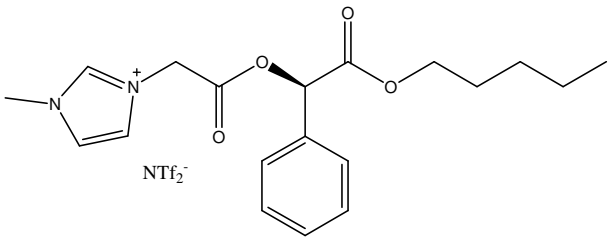
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.86 (s, 1H), 7.35 (m, 5H), 7.31 (t, *J* = 1.6 Hz, 1H), 7.20 – 7.19 (m, 1H), 5.92 (s, 1H), 5.13 (d, *J* = 12.0 Hz, 2H), 4.08 – 4.04 (m, 2H), 3.90 (s, 3H), 1.53 – 1.45 (m, 2H), 1.19 – 1.07 (m, 4H), 0.75 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.99, 165.32, 137.50, 132.48, 129.77, 128.96, 127.70, 124.45, 123.74, 123.47, 121.26 (q, *J* = 320 Hz, 2*C*F_3), 76.42, 66.26, 49.75, 36.48, 27.94, 27.62, 13.83

IR (thin film on salt plate) (cm^{-1}) 3165, 3123, 2959, 2928, 2858, 1751, 1559, 1540, 1495, 1457, 1354, 1198, 1136

MS *m/z*, 345.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

R - 3-Methyl-1-(pentylmandelylcarbonylmethyl)imidazolium NTf_2 (215g)



Brown viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(pentyl mandelyl carbonyl methyl) imidazolium bromide **213g** (1.28 g, 3.00 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 87 % yield (1.64 g, 2.61 mmol)

Molecular formula $C_{21}H_{26}F_6N_3O_8S_2$

Molecular weight 625 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.86 (s, 1H), 7.37 – 7.30 (m, 5H), 7.28 (t, *J* = 1.8 Hz, 1H), 7.20 – 7.19 (m, 1H), 5.92 (s, 1H), 5.13 (d, *J* = 12.8 Hz, 2H), 4.10 – 4.03 (m, 2H), 3.91 (s, 3H), 4.49 (tt, *J* = 7.0, 7.2 Hz, 2H), 1.19 – 1.05 (m, 4H), 0.75 (t, *J* = 7.0 Hz, 3H)

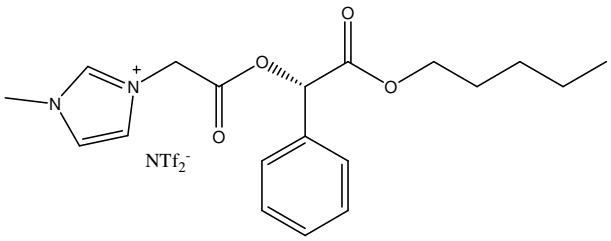
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.02, 165.35, 137.47, 132.48, 129.77, 128.58, 127.69, 123.74, 123.48, 121.27 (q, *J* = 320 Hz, 2*C*F_3), 76.42, 66.26, 49.73, 36.46, 27.71, 27.61, 22.13, 13.82

IR (thin film on salt plate) (cm^{-1}) 3162, 3121, 2961, 2928, 2859, 1751, 1566, 1559, 1540, 1495, 1457, 1354, 1198, 1136

MS *m/z*, 345.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -45.6º (0.6 c, $CHCl_3$)

S - 3-Methyl-1-(pentylmandelylcarbonylmethyl)imidazolium NTf_2 (215h)



Brown viscous liquid

The title compound was prepared from *S* - 3-methyl-1-(pentyl mandelyl carbonyl methyl) imidazolium bromide **213h** (1.06 g, 2.50 mmol) and $LiNTf_2$ (0.86 g, 3.00 mmol) according to the general procedure in 96 % yield (1.49 g, 2.38 mmol)

Molecular formula $C_{21}H_{26}F_6N_3O_8S_2$

Molecular weight 625 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.77 (s, 1H), 7.37 – 7.32 (m, 5H), 7.31 (t, *J* = 1.7 Hz, 1H), 7.22 (t, *J* = 1.7 Hz, 1H), 5.91 (s, 1H), 5.10 (d, *J* = 5.6 Hz, 2H), 4.07 – 4.02 (m, 2H), 3.89 (s, 3H), 1.52 (tt, *J* = 7.0, 7.2 Hz, 2H), 1.19 – 1.04 (m, 4H), 0.74 (t, *J* = 7.2 Hz, 3H)

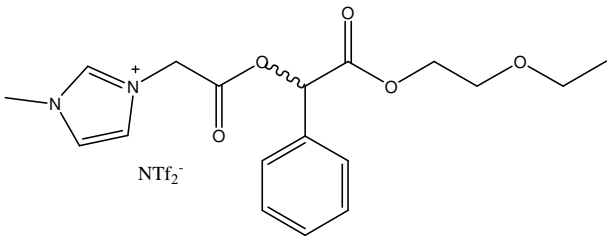
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.00, 165.28, 137.78, 132.37, 129.83, 128.99, 127.74, 123.71, 123.29, 121.19 (q, *J* = 320 Hz, 2*C*F_3), 76.48, 66.32, 49.87, 36.62, 27.96, 27.64, 22.09, 13.86

IR (thin film on salt plate) (cm^{-1}) 3163, 3126, 2958, 2928, 2862, 1751, 1566, 1559, 1539, 1495, 1457, 1354, 1198, 1136

MS *m/z*, 345.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ +45.8º (0.9 c, $CHCl_3$)

_RS_ - 3-Methyl-1-(ethoxyethylmandelylcarbonylmethyl)imidazolium NTf_2 (215l)



Orange viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(ethoxy ethyl mandelyl carbonyl methyl) imidazolium bromide **213l** (1.02 g, 2.40 mmol) and $LiNTf_2$ (0.86 g, 3.00 mmol) according to the general procedure in 79 % yield (1.18 g, 1.88 mmol)

Molecular formula $C_{20}H_{24}F_6N_3O_9S_2$

Molecular weight 627 g/mol

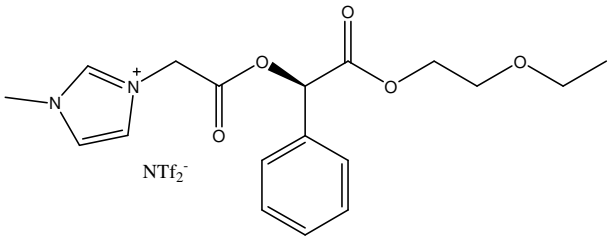
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.79 (s, 1H), 7.39 – 7.33 (m, 6H), 7.22 (t, *J* = 1.6 Hz, 1H), 5.96 (s, 1H), 5.10 (d, *J* = 7.6 Hz, 2H), 4.25 (t, *J* = 4.8 Hz, 2H), 3.87 (s, 3H), 3.51 (t, *J* = 4.8 Hz, 2H), 3.35 (q, *J* = 6.9 Hz, 2H), 1.03 (t, *J* = 6.9 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.84, 165.28, 137.82, 132.12, 129.88, 128.99, 127.83, 123.76, 123.26, 121.27 (d, *J* = 319 Hz, 2*C*F_3), 76.43, 67.81, 66.54, 65.10, 49.87, 36.64, 15.01

IR (thin film on salt plate) (cm^{-1}) 3169, 3122, 2965, 2927, 2859, 1751, 1569, 1559, 1540, 1495, 1457, 1354, 1198, 1136

MS *m/z*, 347.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

_R_ - 3-Methyl-1-(ethoxyethylmandelylcarbonylmethyl)imidazolium NTf_2 (215j)



Orange viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(ethoxy ethyl mandelyl carbonyl methyl) imidazolium bromide **213l** (1.20 g, 2.80 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 92 % yield (1.62 g, 2.57 mmol)

Molecular formula $C_{20}H_{24}F_6N_3O_9S_2$

Molecular weight 627 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.79 (s, 1H), 7.39 – 7.32 (m, 6H), 7.22 (t, *J* = 1.8 Hz, 1H), 5.96 (s, 1H), 5.12 (d, *J* = 7.2 Hz, 2H), 4.25 (t, *J* = 5.0 Hz, 2H), 3.89 (s, 3H), 3.49 (t, *J* = 5.0 Hz, 2H), 3.35 (q, *J* = 7.1 Hz, 2H), 1.03 (t, *J* = 7.1 Hz, 3H)

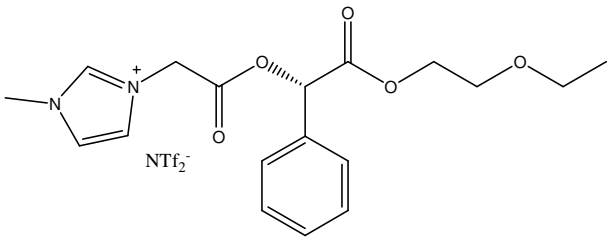
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.85, 165.29, 137.85, 132.12, 129.88, 128.99, 127.83, 123.76, 123.26, 121.25 (d, *J* = 319 Hz, 2*C*F_3), 76.44, 67.81, 66.55, 65.11, 49.88, 36.65, 15.00

IR (thin film on salt plate) (cm^{-1}) 3167, 3120, 2963, 2927, 2860, 1752, 1565, 1559, 1539, 1495, 1457, 1354, 1198, 1136

MS *m/z*, 347.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -46.2º (0.5 c, $CHCl_3$)

_S_ - 3-Methyl-1-(ethoxyethylmandelylcarbonylmethyl)imidazolium NTf_2 (215k)



Brown viscous liquid

The title compound was prepared from *S* - 3-methyl-1-(ethoxy ethyl mandelyl carbonyl methyl) imidazolium bromide **213k** (1.07 g, 2.50 mmol) and $LiNTf_2$ (0.86 g, 3.00 mmol) according to the general procedure in 86 % yield (1.30 g, 2.07 mmol)

Molecular formula $C_{20}H_{24}F_6N_3O_9S_2$

Molecular weight 627 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.84 (s, 1H), 7.47 – 7.40 (m, 6H), 7.32 – 7.31 (m, 1H), 6.04 (s, 1H), 5.18 (d, *J* = 5.2 Hz, 2H), 4.34 (t, *J* = 4.6 Hz, 2H), 3.94 (s, 3H), 3.56 (t, *J* = 4.6 Hz, 2H), 3.44 (q, *J* = 7.0 Hz, 2H), 1.11 (t, *J* = 7.0 Hz, 3H)

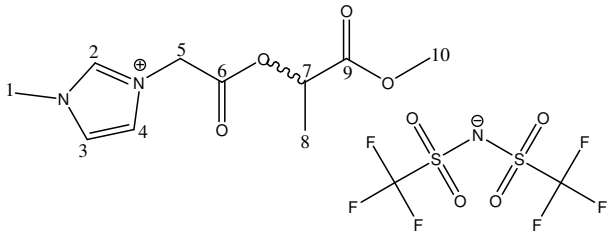
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.86, 165.32, 137.73, 132.14, 129.87, 128.98, 128.58, 123.77, 123.32, 121.29 (q, *J* = 319 Hz, 2*C*F_3), 76.41, 67.80, 66.53, 65.10, 49.83, 36.60, 15.00

IR (thin film on salt plate) (cm^{-1}) 3166, 3122, 2970, 2927, 2858, 1751, 1569, 1559, 1540, 1495, 1456, 1354, 1200, 1136

MS *m/z*, 347.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ +46.7° (0.5 c, $CHCl_3$)

RS - 3-Methyl-1-(methyllactylcarbonylmethyl)imidazolium NTf_2 (216b)



Colourless liquid

The title compound was prepared from *RS* - 3-methyl-1-(methyl lactylcarbonylmethyl) imidazolium bromide **214b** (0.53 g, 1.70 mmol) and $LiNTf_2$ (1.15 g, 4.00 mmol) according to the general procedure in 65 % yield (0.56 g, 1.11 mmol)

Molecular formula $C_{12}H_{16}F_6N_3O_8S_2$

Molecular weight 507 g/mol

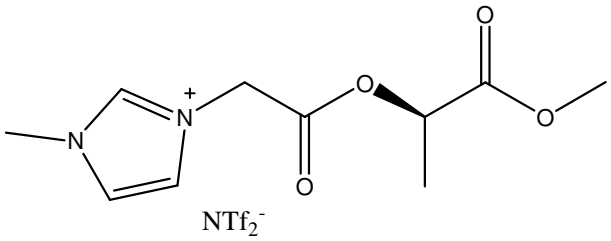
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.76 (s, 1H, *H2*), 7.34 (t, *J* = 1.8 Hz, 1H, *H3*), 7.26 (t, *J* = 1.8 Hz, 1H, *H4*), 5.15 (q, *J* = 7.0 Hz, 1H, *H7*), 5.13 (d, *J* = 18 Hz, 1H, *H5*), 5.02 (d, *J* = 18 Hz, 1H, *H5*), 5.89 (s, 3H, *H1*), 3.69 (s, 3H, *H10*), 1.49 (d, *J* = 7.0 Hz, 3H, *H8*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 170.28 (*C*OO), 165.32 (*C*OO), 137.67 (N*C*HN), 123.81 (N*C*H_2), 123.31 (N*C*H_2), 121.00 (q, *J* = 320 Hz, 2*C*F_3), 70.83 (O*C*H_2), 52.74 (N*C*H_2), 49.77 (O*C*H_3), 36.58 (N*C*H_3), 16.58 (C*C*H_3)

IR (thin film on salt plate) (cm^{-1}) 3166, 3121, 2958, 2926, 2858, 1751, 1569, 1559, 1539, 1495, 1452, 1354, 1192, 1136

MS *m/z*, 227.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

R - 3-Methyl-1-(methyllactylcarbonylmethyl)imidazolium NTf_2 (216a)



Brown viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(methyl lactyl carbonyl methyl) imidazolium bromide **214a** (0.95 g, 3.10 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 57 % yield (0.90 g, 1.78 mmol)

Molecular formula $C_{12}H_{16}F_6N_3O_8S_2$

Molecular weight 507 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.85 (s, 1H), 7.42 (t, *J* = 1.8 Hz, 1H), 7.37 (t, *J* = 1.8 Hz, 1H), 5.24 -5.17 (m, 2H), 5.10 (d, *J* = 18 Hz, 1H), 3.98 (s, 3H), 3.77 (s, 3H), 1.57 (d, *J* = 6.8 Hz, 3H)

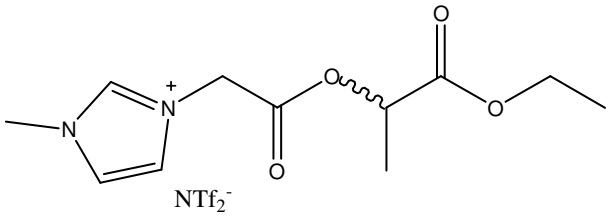
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 170.24, 165.28, 137.69, 123.79, 123.30, 121.29 (q, *J* = 320 Hz, 2*C*F_3), 70.84, 52.73, 49.78, 36.59, 16.58

IR (thin film on salt plate) (cm^{-1}) 3165, 3124, 2962, 2924, 2860, 1751, 1581, 1569, 1559, 1495, 1453, 1354, 1198, 1136

MS *m/z*, 227.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -29.1° (0.7 c, $CHCl_3$)

RS - 3-Methyl-1-(ethyllactylcarbonylmethyl)imidazolium NTf_2 (216d)



Brown viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(ethyl lactyl carbonyl methyl) imidazolium bromide **214d** (1.00 g, 3.1 mmol) and $LiNTf_2$ (1.15 g, 4.00 mmol) according to the general procedure in 63 % yield (1.01 g, 1.94 mmol)

Molecular formula $C_{13}H_{18}F_6N_3O_8S_2$

Molecular weight 521 g/mol

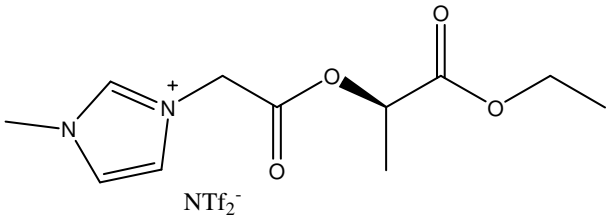
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.79 (s, 1H), 7.33 (t, *J* = 1.6 Hz, 1H), 7.25 (t, *J* = 1.6 Hz, 1H), 5.12 (m, 2H), 5.01 (d, *J* = 18 Hz, 1H), 4.17 (q, *J* = 7.0 Hz, 2H), 3.90 (s, 3H), 1.49 (d, *J* = 7.0 Hz, 3H), 1.20 (t, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.82, 165.28, 137.75, 123.78, 123.27, 121.22 (q, *J* = 320 Hz, 2*C*F_3), 70.96, 61.98, 49.83, 36.63, 16.58, 14.03

IR (thin film on salt plate) (cm^{-1}) 3165, 3127, 2966, 2927, 2860, 1751, 1569, 1559, 1495, 1452, 1354, 1197, 1136

MS *m/z*, 241.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

R - 3-Methyl-1-(ethyllactylcarbonylmethyl)imidazolium NTf_2 (216c)



Brown viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(ethyl lactyl carbonyl methyl) imidazolium bromide **214c** (0.96 g, 3.00 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 72 % yield (1.13 g, 2.17 mmol)

Molecular formula $C_{13}H_{18}F_6N_3O_8S_2$

Molecular weight 521 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.79 (s, 1H), 7.33 (t, *J* = 1.8 Hz, 1H), 7.25 (t, *J* = 1.8 Hz, 1H), 5.14 (d, *J* = 18 Hz, 1H), 5.12 (q, *J* = 7.2 Hz, 1H), 5.01 (d, *J* = 18 Hz, 1H), 4.17 (q, *J* = 7.2 Hz, 2H), 3.90 (s, 3H), 1.49 (d, *J* = 7.2 Hz, 3H), 1.21 (t, *J* = 7.2 Hz, 3H)

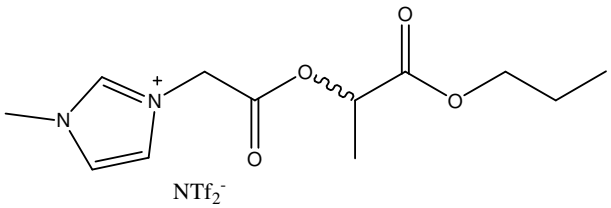
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.82, 165.27, 137.74, 123.78, 123.27, 121.29 (d, *J* = 319 Hz, 2*C*F_3), 70.96, 61.97, 49.83, 36.62, 16.57, 14.02

IR (thin film on salt plate) (cm^{-1}) 3164, 3121, 2961, 2927, 2860, 1751, 1582, 1569, 1559, 1495, 1452, 1353, 1197, 1136

MS *m/z*, 241.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -28.5º (0.6 c, $CHCl_3$)

RS - 3-Methyl-1-(propyllactylcarbonylmethyl)imidazolium NTf_2 (216f)



Yellow viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(propyl lactyl carbonyl methyl) imidazolium bromide **214f** (1.12 g, 3.30 mmol) and $LiNTf_2$ (1.06 g, 3.70 mmol) according to the general procedure in 86 % yield (1.51 g, 2.82 mmol)

Molecular formula $C_{14}H_{20}F_6N_3O_8S_2$

Molecular weight 535 g/mol

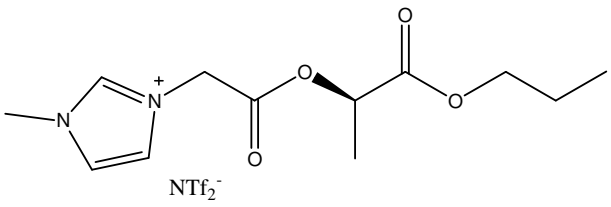
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.75 (s, 1H), 7.33 (t, *J* = 1.8 Hz, 1H), 7.27 (t, *J* = 1.8 Hz, 1H), 5.14 – 5.08 (m, 2H), 5.00 (d, *J* = 18 Hz, 1H), 4.06 – 4.01 (m, 2H), 3.89 (s, 3H), 1.64 (tq, *J* = 7.2, 7.4 Hz, 2H), 1.49 (d, *J* = 7.2 Hz, 3H), 0.86 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.89, 165.28, 137.61, 123.78, 123.36, 121.32 (q, *J* = 319 Hz, 2*C*F_3), 70.93, 67.40, 49.79, 36.56, 21.80, 16.61, 10.17

IR (thin film on salt plate) (cm^{-1}) 3163, 3122, 2970, 2927, 2858, 1751, 1569, 1559, 1495, 1452, 1353, 1198, 1136

MS *m/z*, 255.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

R - 3-Methyl-1-(propyllactylcarbonylmethyl)imidazolium NTf_2 (216e)



Brown viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(propyl lactyl carbonyl methyl) imidazolium bromide **214e** (1.01 g, 3.00 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 92 % yield (1.47 g, 2.75 mmol)

Molecular formula $C_{14}H_{20}F_6N_3O_8S_2$

Molecular weight 535 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.83 (s, 1H), 7.31 (t, *J* = 1.8 Hz, 1H), 7.23 (t, *J* = 1.8 Hz, 1H), 5.17-5.14 (m, 2H), 5.00 (d, *J* = 18 Hz, 1H), 4.05 (t, *J* = 6.6 Hz, 2H), 3.91 (s, 3H), 1.65 – 1.56 (m, 2H), 1.50 (d, *J* = 7.2 Hz, 3H), 0.87 (t, *J* = 7.4 Hz, 3H)

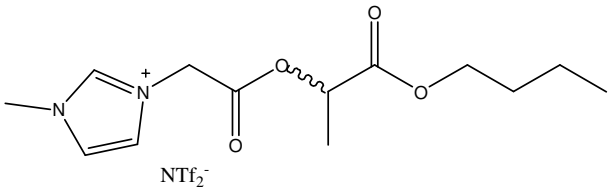
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.87, 165.23, 137.89, 123.74, 123.19, 121.19 (q, J = 319 Hz, 2*C*F_3), 70.97, 67.44, 49.89, 36.68, 21.83, 16.63, 10.20

IR (thin film on salt plate) (cm^{-1}) 3165, 3122, 2964, 2927, 2857, 1751, 1568, 1559, 1495, 1472, 1452, 1354, 1198, 1136

MS *m/z*, 255.1 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -26.3º (0.7 c, $CHCl_3$)

_RS_ - 3-Methyl-1-(butyllactylcarbonylmethyl)imidazolium NTf_2 (216h)



Brown viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(butyl lactyl carbonyl methyl) imidazolium bromide **214h** (1.11 g, 3.18 mmol) and $LiNTf_2$ (1.21 g, 4.20 mmol) according to the general procedure in 83 % yield (1.46 g, 2.65 mmol)

Molecular formula $C_{15}H_{22}F_6N_3O_8S_2$

Molecular weight 549 g/mol

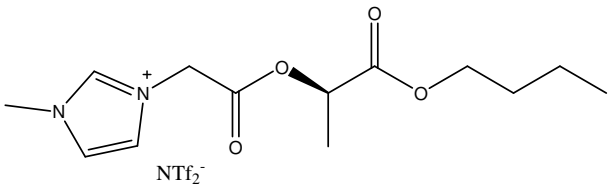
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.81 (s, 1H), 7.32 (s, 1H), 7.24 (s, 1H), 5.13 (d, *J* = 18 Hz, 1H), 5.11 (q, *J* = 7.0 Hz, 1H), 5.00 (d, *J* = 18 Hz, 1H), 4.09 (t, *J* = 7.0 Hz, 2H), 3.90 (s, 3H), 1.54 (m, 2H), 1.49 (d, *J* = 7.0 Hz, 3H), 1.30 (tq, *J* = 7.2, 7.4 Hz, 2H), 0.86 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.88, 165.25, 137.79, 123.76, 123.25, 121.29 (q, *J* = 319 Hz, 2*C*F_3), 70.94, 65.77, 49.86, 36.66, 30.42, 18.96, 16.63, 13.63

IR (thin film on salt plate) (cm^{-1}) 3167, 3121, 2966, 2935, 2860, 1751, 1581, 1569, 1559, 1495, 1452, 1354, 1198, 1136

MS *m/z*, 269.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

R - 3-Methyl-1-(butyllactylcarbonylmethyl)imidazolium NTf_2 (216g)



Brown viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(butyl lactyl carbonyl methyl) imidazolium bromide **214g** (0.77 g, 2.20 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 64 % yield (0.78 g, 1.41 mmol)

Molecular formula $C_{15}H_{22}F_6N_3O_8S_2$

Molecular weight 549 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.84 (s, 1H), 7.32 (t, *J* = 1.6 Hz, 1H), 7.23 (t, *J* = 1.6 Hz, 1H), 5.17 (d, *J* = 17.6 Hz, 1H), 5.13 (q, *J* = 7.0 Hz, 1H), 5.01 (d, *J* = 17.6 Hz, 1H), 4.09 (t, *J* = 6.4 Hz, 2H), 3.91 (s, 3H), 1.62-1.57 (m, 2H), 1.50 (d, *J* = 7.0 Hz, 3H), 1.31 (tq, *J* = 7.4 Hz, 7.6 Hz, 2H), 0.86 (t, *J* = 7.6 Hz, 3H)

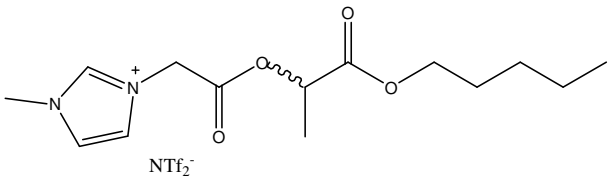
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.88, 165.23, 137.88, 123.74, 123.19, 121.25 (q, *J* = 319 Hz, 2*C*F_3), 70.96, 65.78, 49.88, 36.68, 30.43, 18.97, 16.63, 13.63

IR (thin film on salt plate) (cm^{-1}) 3166, 3122, 2966, 2934, 2863, 1751, 1569, 1559, 1495, 1452, 1354, 1201, 1135

MS *m/z*, 269.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -25.5º (0.6 c, $CHCl_3$)

RS - 3-Methyl-1-(pentyllactylcarbonylmethyl)imidazolium NTf_2 (216j)



Pale brown viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(pentyl lactyl carbonyl methyl) imidazolium bromide **214j** (1.02 g, 2.80 mmol) and $LiNTf_2$ (1.21 g, 4.20 mmol) according to the general procedure in 87 % yield (1.36 g, 2.42 mmol)

Molecular formula $C_{16}H_{24}F_6N_3O_8S_2$

Molecular weight 563 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.75 (s, 1H), 7.33 (t, *J* = 1.8 Hz, 1H), 7.27 (t, *J* = 1.8 Hz, 1H), 5.10 (m, 2H), 5.04 (d, *J* = 18 Hz, 1H), 4.07 (t, *J* = 7.0 Hz, 2H), 3.89 (s,

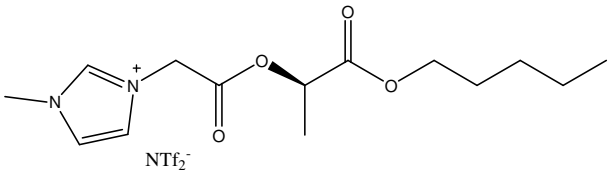
3H), 1.57 (tt, *J* = 7.0, 7.2 Hz, 2H), 1.49 (d, *J* = 7.2 Hz, 3H), 1.25-1.20 (m, 4H), 0.83 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.91, 165.29, 137.61, 123.79, 123.36, 121.32 (q, *J* = 319 Hz, 2*C*F_3), 70.90, 66.03, 49.79, 36.57, 28.08, 27.82, 22.21, 16.61, 13.92

IR (thin film on salt plate) (cm^{-1}) 3164, 3124, 2962, 2934, 2860, 1750, 1582, 1569, 1559, 1495, 1456, 1354, 1198, 1136

MS *m/z*, 283.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

R - 3-Methyl-1-(pentyllactylcarbonylmethyl)imidazolium NTf_2 (216i)



Yellow viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(pentyl lactyl carbonyl methyl) imidazolium bromide **214i** (1.09 g, 3.00 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 87 % yield (1.47 g, 2.61 mmol)

Molecular formula $C_{16}H_{24}F_6N_3O_8S_2$

Molecular weight 563 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.76 (s, 1H), 7.33 (t, *J* = 1.8 Hz, 1H), 7.26 (t, *J* = 1.8 Hz, 1H), 5.14 (q, *J* = 7.2 Hz, 1H), 5.13 (d, *J* = 18 Hz, 1H), 5.00 (d, *J* = 18 Hz, 1H), 4.10 – 4.04 (t, *J* = 7.0 Hz, 2H), 3.89 (s, 3H), 1.61 (tt, *J* =7.0, 7.2 Hz, 2H), 1.49 (d, *J* = 7.2 Hz, 3H), 1.29 – 1.22 (m, 4H), 0.83 (t, *J* = 7.2 Hz, 3H)

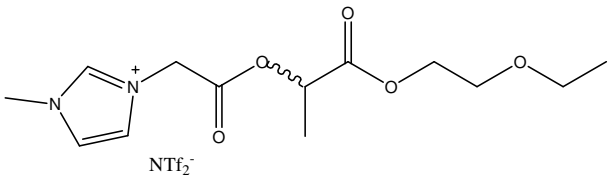
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.89, 165.26, 137.66, 123.77, 123.32, 121.30 (q, *J* = 319 Hz, 2*C*F_3), 70.91, 66.03, 49.81, 36.58, 28.08, 27.82, 22.20, 16.61, 13.91

IR (thin film on salt plate) (cm^{-1}) 3167, 3123, 2962, 2934, 2863, 1750, 1569, 1559, 1495, 1452, 1436, 1354, 1197, 1136

MS *m/z*, 283.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -28.2º (0.7 c, $CHCl_3$)

RS - 3-Methyl-1-(ethoxyethyllactylcarbonylmethyl)imidazolium NTf_2 (216l)



Yellow viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(ethoxy ethyl lactyl carbonyl methyl) imidazolium bromide **214l** (1.13 g, 3.10 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 76 % yield (1.33 g, 2.35 mmol)

Molecular formula $C_{15}H_{22}F_6N_3O_9S_2$

Molecular weight 565 g/mol

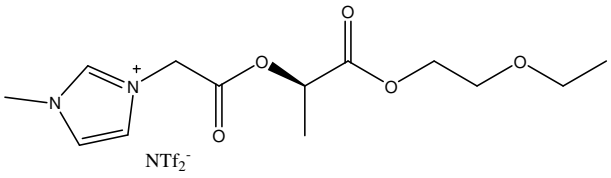
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.78 (s, 1H), 7.35 (t, *J* = 1.8 Hz, 1H), 7.25 (t, *J* = 1.8 Hz, 1H), 5.18 – 5.10 (m, 2H), 5.01 (d, *J* = 17.6 Hz, 1H), 4.29 – 4.17 (m, 2H), 3.90 (s, 3H), 3.57 (t, *J* = 4.8 Hz, 2H), 3.48 (q, *J* = 6.8 Hz, 2H), 1.50 (d, *J* = 6.8 Hz, 3H), 1.12 (t, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.78, 165.29, 137.71, 123.83, 123.29, 121.29 (q, *J* = 319 Hz, 2*C*F_3), 70.90, 67.91, 66.59, 64.74, 49.82, 36.60, 16.56, 15.06

IR (thin film on salt plate) (cm^{-1}) 3166, 3123, 2959, 2927, 2859, 1751, 1569, 1559, 1495, 1451, 1354, 1198, 1134

MS *m/z*, 285.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

R - 3-Methyl-1-(ethoxyethyllactylcarbonylmethyl)imidazolium NTf_2 (216k)



Yellow viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(ethoxy ethyl lactyl carbonyl methyl) imidazolium bromide **214k** (1.10 g, 3.00 mmol) and $LiNTf_2$ (1.00 g, 3.50 mmol) according to the general procedure in 67 % yield (1.14 g, 2.02 mmol)

Molecular formula $C_{15}H_{22}F_6N_3O_9S_2$

Molecular weight 565 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 8.77 (s, 1H), 7.35 (t, *J* = 1.8 Hz, 1H), 7.26 (t, *J* = 1.8 Hz, 1H), 5.17 – 5.09 (m, 2H), 5.01 (d, *J* = 18 Hz, 1H), 4.28 – 4.17 (m, 2H), 3.89 (s, 3H), 3.57 (t, *J* = 4.6 Hz, 2H), 3.48 (q, *J* = 6.9 Hz, 2H), 1.50 (d, *J* = 7.2 Hz, 3H), 1.12 (t, *J* = 6.9 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.80, 165.30, 137.66, 123.84, 123.32, 121.30 (q, J = 319 Hz, 2*C*F_3), 70.89, 67.91, 66.58, 64.74, 49.81, 36.58, 16.55, 15.07

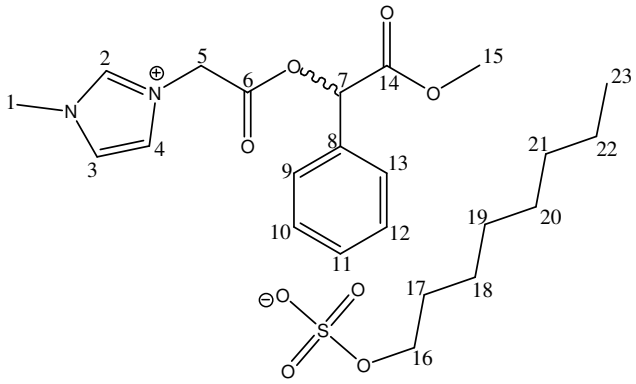
IR (thin film on salt plate) (cm^{-1}) 3170, 3122, 2962, 2927, 2863, 1751, 1582, 1569, 1559, 195, 1453, 1354, 1198, 1136

MS *m/z*, 285.2 $[M\text{-}NTf_2^-]^+$; MS: *m/z*, 280.0 $[NTf_2^-]$

$[\alpha]_D^{20}$ -22.5º (0.7 c, $CHCl_3$)

Chiral $OctOSO_3^-$ salts

Representative procedure for the preparation of chiral $OctOSO_3$ salts (*RS* - 3-methyl-1-(methylmandelylcarbonylmethyl)imidazolium $OctOSO_3$) (217o)



To a stirred solution of *RS* – 3 – methyl -1- (methyl mandelyl carbonyl methyl) imidazolium bromide **213o** (2.50 mmol, 0.92 g) in distilled water (20 mL) was added in one portion sodium octyl sulfate (2.60 mmol, 0.60 g). The mixture was left stirring overnight, then the water was evaporated on the rotary evaporator. The remaining product was dissolved in DCM (10 mL) and washed with water (2 x 2 mL). The product was then dried on the rotary evaporator and under high vacuum for 8 h to give a pale brown solid at RT in 97 % yield (0.89 g, 1.78 mmol)

Molecular formula $C_{23}H_{34}N_2O_8S_2$

Molecular weight 498 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.24 (s, 1H, *H2*), 7.48 (t, *J* = 1.6 Hz, 1H, *H4*), 7.42 (t, *J* = 1.6 Hz, 1H, *H3*), 7.36-7.30 (m, 5H, *H's 9-13*), 5.91 (s, 1H, *H7*), 5.32 (d, *J* = 17.8 Hz, 1H, *H5*), 5.24 (d, *J* = 17.8 Hz, 1H, *H5*), 3.88-3.83 (m, 5H, *H's 15 and 16*), 3.61 (s 3H, *H1*), 1.52 (tt, *J* = 7.2 Hz, 7.2 Hz, 2H, *H17*), 1.22-1.12 (m, 10H, *H's 18-22*), 0.81 (t, *J* = 7.2 Hz, 3H, *H23*)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.50 (*C*OO), 165.11 (*C*OO), 137.55 (N*C*HN), 131.54 (Ar*C*), 128.68 (Ar*C*), 127.93 (Ar*C*), 126.75 (Ar*C*), 122.81 (N*C*H_2), 122.45 (N*C*H_2), 75.08 (*C*H), 66.75 (O*C*H_3), 51.89 (O*C*H_2), 48.65 (N*C*H_2), 35.40 (*C*H_2),

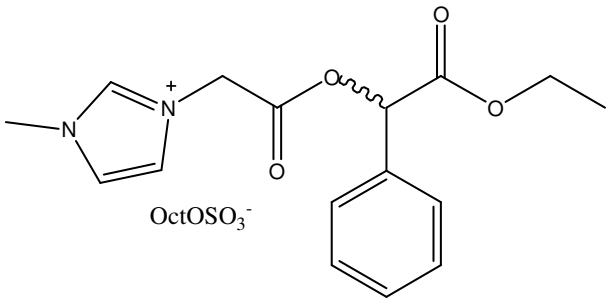
30.78 (N*C*H$_3$), 28.44 (*C*H$_2$), 28.31 (*C*H$_2$), 28.22 (*C*H$_2$), 24.81 (*C*H$_2$), 21.62 (*C*H$_2$), 13.10 (*C*H$_3$)

MP (°C) 61 – 62

IR (KBr disc) (cm^{-1}) 3159, 3125, 2963, 2932, 2850, 1740, 1552, 1531, 1495, 1454, 1399, 1210, 1177

MS *m/z*, 289.1188 [M-OctOSO$_3^-$]$^+$; MS: *m/z*, 209.1 [OctOSO$_3^-$]

_RS_ - 3-Methyl-1-(ethylmandelylcarbonylmethyl)imidazolium OctOSO$_3$ (217c)



Yellow grease

The title compound was prepared from *RS* - 3-methyl-1-(ethyl mandelyl carbonyl methyl) imidazolium bromide **213c** (2.50 mmol, 0.94 g) and sodium octyl sulfate (2.60 mmol, 0.60 g) according to the general procedure in 92 % yield (1.18 g, 2.30 mmol)

Molecular formula $C_{24}H_{36}N_2O_8S_2$

Molecular weight 512 g/mol

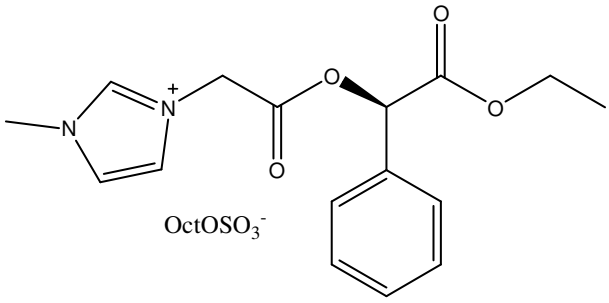
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.46 (s, 1H), 7.48 (t, *J* = 1.6 Hz, 1H), 7.44-7.33 (m, 5H), 7.36 (t, *J* = 1.6 Hz, 1H), 5.99 (s, 1H), 5.48 (d, *J* =18 Hz, 1H), 5.33 (d, *J* = 18 Hz, 1H), 4.19-4.09 (m, 2H), 3.98 (s, 3H), 1.63 (m, 2H), 1.31-1.19 (m, 12H), 1.22 (t, *J* = 7.0 Hz, 3H), 0.88 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.02, 165.93, 138.85, 132.50, 129.72, 128.58, 127.79, 123.62, 123.11, 76.29, 68.24, 62.22, 49.90, 36.67, 31.82, 29.39, 29.32, 29.25, 25.80, 22.66, 14.13, 13.97

IR (thin film on salt plate) (cm^{-1}) 2958, 2927, 2857, 1748, 1559, 1539, 1495, 1452, 1401, 1202, 1176

MS *m/z*, 303.1 [M-OctOSO$_3^-$]$^+$; MS: *m/z*, 209.1 [OctOSO$_3^-$]

_R_ - 3-Methyl-1-(ethylmandelylcarbonylmethyl)imidazolium $OctOSO_3$ (217a)



Pale brown solid

The title compound was prepared from *R* - 3-methyl-1-(ethyl mandelyl carbonyl methyl) imidazolium bromide **213a** (2.50 mmol, 0.95 g) and sodium octyl sulfate (2.60 mmol, 0.60 g) according to the general procedure in 95 % yield (1.22 g, 2.39 mmol)

Molecular formula $C_{24}H_{36}N_2O_8S_2$

Molecular weight 512 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.46 (s, 1H), 7.39 (t, *J* = 1.6 Hz, 1H), 7.34-7.24 (m, 5H), 7.28 (t, *J* = 1.6 Hz, 1H), 5.90 (s, 1H), 5.41 (d, *J* = 18 Hz, 1H), 5.25 (d, *J* = 18 Hz, 1H), 4.13-3.98 (m, 2H), 3.90 (s, 3H), 1.54 (tt, *J* = 7.2, 7.4 Hz, 2H), 1.21-1.13 (m, 12H), 1.13 (t, *J* = 7.4 Hz, 3H), 0.80 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.03, 165.94, 138.95, 132.48, 129.73, 128.58, 126.55, 123.60, 123.07, 76.29, 68.08, 62.23, 49.88, 36.65, 31.83, 29.42, 29.33, 29.25, 25.81, 22.67, 14.14, 13.98

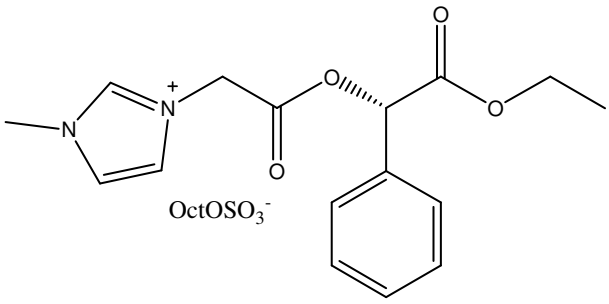
MP (°C) 40 – 42

IR (KBr disc) (cm^{-1}) 3160, 3120, 2956, 2927, 2856, 1751, 1565, 1559, 1539, 1495, 1456, 1403, 1205, 1177

MS *m/z*, 303.1 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.1 $[OctOSO_3^-]$

$[\alpha]_D^{20}$ -44.5º (0.8 c, Acetone)

_S_ - 3-Methyl-1-(ethylmandelylcarbonylmethyl)imidazolium $OctOSO_3$ (217b)



Pale brown solid

The title compound was prepared from *S* - 3-methyl-1-(ethyl mandelyl carbonyl methyl) imidazolium bromide **213b** (2.60 mmol, 1.00 g) and sodium octyl sulfate (2.70 mmol, 0.63 g) according to the general procedure in 91 % yield (1.21 g, 2.36 mmol)

Molecular formula $C_{24}H_{36}N_2O_8S_2$

Molecular weight 512 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.40 (s, 1H), 7.35-7.28 (m, 6H), 7.26 (s, 1H), 5.90 (s, 1H), 5.38 (d, *J* = 18 Hz, 1H), 5.22 (d, *J* = 18 Hz, 1H), 4.10-4.02 (m, 2H), 3.90 (s, 3H), 1.54-1.49 (m, 2H), 1.17-1.12 (m, 15H), 0.80 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.99, 165.90, 139.09, 132.48, 129.72, 128.97, 127.80, 123.56, 123.03, 76.31, 68.15, 62.21, 49.87, 36.63, 31.82, 29.41, 29.33, 29.25, 25.81, 22.66, 14.13, 13.97

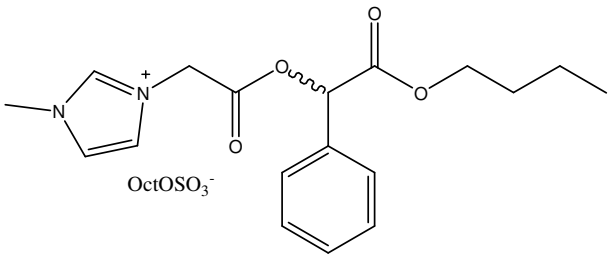
MP (°C) 38 – 40

IR (KBr disc) (cm^{-1}) 3163, 3116, 2956, 2927, 2856, 1748, 1566, 1559, 1494, 1457, 1399, 1213, 1177

MS *m/z*, 303.1 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.1 $[OctOSO_3^-]$

$[\alpha]_D^{20}$ +43.8º (0.7 c, Acetone)

RS - 3-Methyl-1-(butylmandelylcarbonylmethyl)imidazolium $OctOSO_3$ (217f)



Brown viscous liquid

The title compound was prepared from *RS* - 3-methyl-1-(butyl mandelyl carbonyl methyl) imidazolium bromide **213f** (2.40 mmol, 1.00 g) and sodium octyl sulfate (2.50 mmol, 0.59 g) according to the general procedure in 99 % yield (1.29 g, 2.38 mmol)

Molecular formula $C_{26}H_{40}N_2O_8S_2$

Molecular weight 540 g/mol

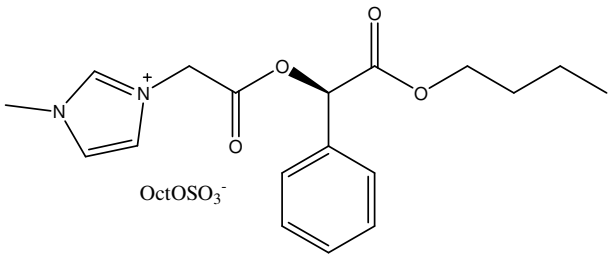
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.37 (s, 1H), 7.33-7.22 (m, 6H), 7.27 (t, *J* = 1.6 Hz, 1H), 5.91 (s, 1H), 5.39 (d, *J* = 18.2 Hz, 1H), 5.23 (d, *J* = 18.2 Hz, 1H), 4.06-3.93 (m, 2H), 3.90 (s, 3H), 1.49-1.40 (m, 4H), 2.00-1.91 (m, 13H), 0.80 (t, *J* = 5.8 Hz, 2H), 0.77 (t, *J* = 6.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.10, 165.91, 138.98, 132.53, 129.70, 128.94, 127.75, 123.56, 123.06, 76.24, 68.17, 65.96, 49.88, 36.64, 31.83, 30.31, 29.40, 29.33, 29.25, 25.80, 22.67, 18.81, 14.13, 13.54

IR (thin film on salt plate) (cm^{-1}) 3163, 3117, 2955, 2928, 2860, 1751, 1565, 1559, 1539, 1495, 1456, 1399, 1210, 1177

MS *m/z*, 331.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

R - 3-Methyl-1-(butylmandelylcarbonylmethyl)imidazolium $OctOSO_3$ (217d)



Yellow grease

The title compound was prepared from *R* - 3-methyl-1-(butyl mandelyl carbonyl methyl) imidazolium bromide **213d** (2.40 mmol, 0.99 g) and sodium octyl sulfate (2.50 mmol, 0.58 g) according to the general procedure in 98 % yield (1.26 g, 2.34 mmol)

Molecular formula $C_{26}H_{40}N_2O_8S_2$

Molecular weight 540 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.51 (s, 1H), 7.40 (t, *J* = 1.7 Hz, 1H), 7.34-7.27 (m, 5H), 7.30 (t, *J* = 1.7 Hz, 1H), 5.90 (s, 1H), 5.45 (d, *J* = 18 Hz, 1H), 5.26 (d, *J* = 17.6 Hz, 1H), 4.05-3.92 (m, 2H), 3.91 (s, 3H), 1.47 -1.39 (m, 4H), 1.18-1.06 (m, 12H), 0.80 (t, *J* = 5.8 Hz, 3H), 0.77 (t, *J* = 6.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.11, 165.90, 138.93, 132.52, 128.96, 127.76, 126.52, 123.61, 123.07, 76.26, 67.96, 65.97, 49.92, 36.68, 31.83, 30.31, 29.45, 29.35, 29.27, 25.83, 22.68, 18.81, 14.14, 13.56

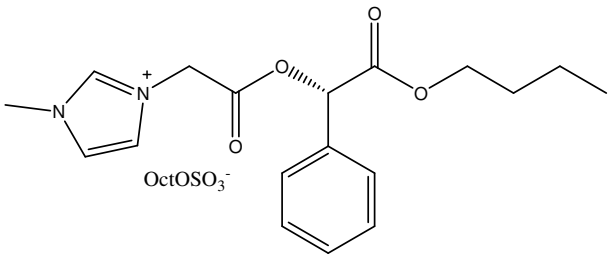
MP 32 - 35

IR (thin film on salt plate) (cm^{-1}) 3158, 3121, 2957, 2937, 2859, 1751, 1565, 1559, 1539, 1495, 1456, 1259, 1217, 1176

MS *m/z*, 331.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

$[\alpha]_D^{20}$ -42.9º (0.5 c, Acetone)

_S_ - 3-Methyl-1-(butylmandelylcarbonylmethyl)imidazolium $OctOSO_3$ (217e)



Pale brown grease

The title compound was prepared from *S* - 3-methyl-1-(butyl mandelyl carbonyl methyl) imidazolium bromide **213e** (2.40 mmol, 0.99 g) and sodium octyl sulfate (2.50 mmol, 0.59 g) according to the general procedure in 77 % yield (1.00 g, 1.85 mmol)

Molecular formula $C_{26}H_{40}N_2O_8S_2$

Molecular weight 540 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.40 (s, 1H), 7.34-7.26 (m, 7H), 5.90 (s, 1H), 5.40 (d, *J* = 18 Hz, 1H), 5.23 (d, *J* = 18 Hz, 1H), 4.06-3.94 (m, 2H), 3.90 (s, 3H), 1.49-1.40 (m, 4H), 1.17-1.04 (m, 12H), 0.78-0.75 (m, 6H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.09, 165.89, 138.99, 132.53, 128.54, 127.75, 126.50, 123.55, 123.04, 76.26, 68.24, 65.96, 49.89, 36.64, 31.83, 30.31, 29.39, 29.32, 29.25, 25.80, 22.67, 18.81, 14.13, 13.54

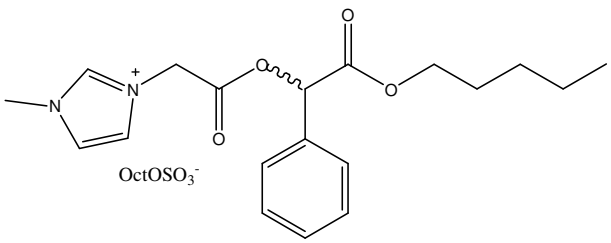
MP (°C) 30 - 32

IR (thin film on salt plate) (cm^{-1}) 3160, 3119, 2957, 2928, 2859, 1751, 1565, 1559, 1539, 1495, 1457, 1260, 1217, 1176

MS *m/z*, 331.2 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.1 $[OctOSO_3^-]$

$[\alpha]_D^{20}$ +42.5º (0.6 c, Acetone)

_RS_ - 3-Methyl-1-(pentylmandelylcarbonylmethyl)imidazolium $OctOSO_3$ (217i)



Brown solid

The title compound was prepared from *RS* - 3-methyl-1-(pentyl mandelyl carbonyl methyl) imidazolium bromide **213i** (2.40 mmol, 1.01 g) and sodium octyl sulfate (2.50 mmol, 0.59 g) according to the general procedure in 95 % yield (1.27 g, 2.29 mmol)

Molecular formula $C_{27}H_{42}N_2O_8S_2$

Molecular weight 554 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.41 (s, 1H), 7.34-7.22 (m, 6H), 7.26 (t, *J* = 1.6 Hz, 1H), 5.91 (s, 1H), 5.41 (d, *J* = 18 Hz, 1H), 5.23 (d, *J* = 18 Hz, 1H), 4.04 (t, *J* = 6.6 Hz, 2H), 3.91 (s, 3H), 1.52-1.44 (m, 4H), 1.12-1.01 (m, 14H), 0.80 (t, *J* = 6.8 Hz, 3H), 0.76 (t, *J* = 7.0 Hz, 3H)

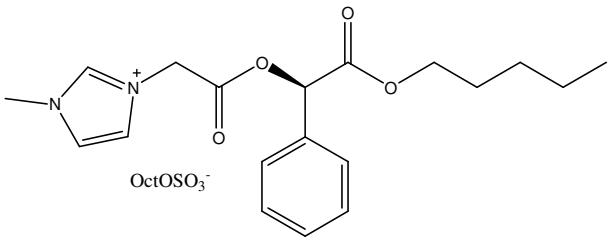
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.08, 165.86, 139.03, 132.53, 129.71, 128.94, 127.75, 123.54, 123.00, 76.26, 68.27, 66.21, 49.90, 36.66, 31.83, 29.39, 29.32, 29.25, 27.99, 27.66, 25.79, 22.67, 22.11, 14.13, 13.89

MP (°C) 30 – 32

IR (KBr disc) (cm^{-1}) 3158, 3118, 2957, 2928, 2859, 1751, 1559, 1539, 1495, 1457, 1404, 11203, 1176

MS *m/z*, 345.3 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.1 $[OctOSO_3^-]$

_R_ - 3-Methyl-1-(pentylmandelylcarbonylmethyl)imidazolium $OctOSO_3$ (217g)



Brown solid

The title compound was prepared from *R* - 3-methyl-1-(pentyl mandelyl carbonyl methyl) imidazolium bromide **213g** (2.60 mmol, 1.10 g) and sodium octyl sulfate (2.70 mmol, 0.64 g) according to the general procedure in 99 % yield (1.43 g, 2.58 mmol)

Molecular formula $C_{27}H_{42}N_2O_8S_2$

Molecular weight 554 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.47 (s, 1H), 7.35-7.23 (m, 6H), 7.24 (s, 1H), 5.91 (s, 1H), 5.42 (d, *J* =18 Hz, 1H), 5.22 (d, *J* = 18 Hz, 1H), 4.05 (s, 2H), 3.91 (s, 3H), 1.52-1.41 (m, 4H), 1.13-1.02 (m, 14H), 0.81 (t, *J* = 6.8 Hz, 3H), 0.75 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.06, 165.81, 139.19, 132.50, 129.72, 128.94, 127.76, 123.50, 122.94, 76.29, 68.25, 66.21, 49.92, 36.68, 31.83, 29.40, 29.32, 29.25, 28.00, 27.66, 25.80, 22.67, 22.11, 14.13, 13.89

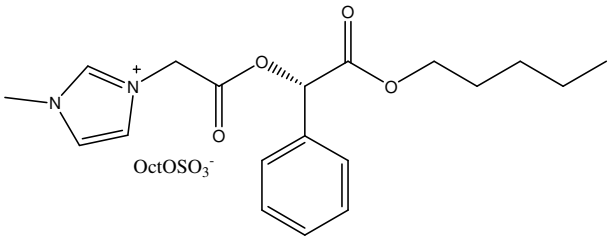
MP (°C) 29 – 31

IR (KBr disc) (cm^{-1}) 3161, 3118, 2954, 2928, 2859, 1751, 1559, 1439, 1456, 1402, 1375, 1217, 1176

MS *m/z*, 345.3 [M-OctOSO$_3^-$]$^+$; MS: *m/z*, 209.1 [OctOSO$_3^-$]

$[\alpha]_D^{20}$ -36.1º (0.7 c, Acetone)

S - 3-Methyl-1-(pentylmandelylcarbonylmethyl)imidazolium OctOSO$_3$ (217h)



Brown viscous liquid

The title compound was prepared from *S* - 3-methyl-1-(pentyl mandelyl carbonyl methyl) imidazolium bromide **213h** (2.40 mmol, 1.04 g) and sodium octyl sulfate (2.50 mmol, 0.59 g) according to the general procedure in 99 % yield (1.32 g, 2.38 mmol)

Molecular formula $C_{27}H_{42}N_2O_8S_2$

Molecular weight 554 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.44 (s, 1H), 7.34 (m, 6H), 7.26 (s, 1H), 5.91 (s, 1H), 5.42 (d, *J* = 18 Hz, 1H), 5.23 (d, *J* = 18 Hz, 1H), 4.04 (t, *J* = 6.6 Hz, 2H), 3.91 (t, *J* = 6.8 Hz, 3H), 1.51-1.43 (m, 4H), 1.17-1.13 (m, 14H), 0.80 (t, *J* = 6.6 Hz, 3H), 0.75 (t, *J* = 7.0 Hz, 3H)

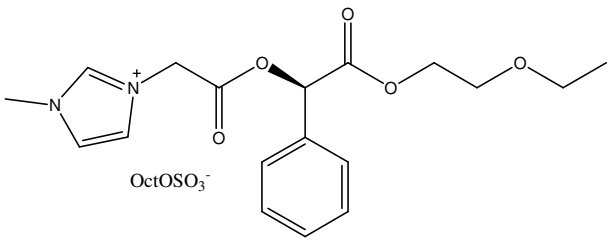
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 168.07, 165.81, 139.04, 135.00, 129.72, 128.95, 127.76, 123.55, 123.00, 76.29, 68.20, 66.22, 49.95, 36.71, 31.83, 29.40, 29.33, 29.25, 28.00, 27.66, 25.80, 22.67, 22.11, 14.13, 13.89

IR (thin film on salt plate) (cm^{-1}) 3166, 3118, 2954, 2928, 2859, 1746, 1566, 1559, 1496, 1456, 1398, 1364, 1205, 1178

MS *m/z*, 345.3 [M-OctOSO$_3^-$]$^+$; MS: *m/z*, 209.1 [OctOSO$_3^-$]

$[\alpha]_D^{20}$ +35.0º (0.7 c, Acetone)

_R_ - 3-Methyl-1-(ethoxyethylmandelylcarbonylmethyl)imidazolium $OctOSO_3$ (217j)



Brown viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(ethoxy ethyl mandelyl carbonyl methyl) imidazolium bromide **213j** (2.40 mmol, 1.04 g) and sodium octyl sulfate (2.60 mmol, 0.60 g) according to the general procedure in 82 % yield (1.09 g, 1.96 mmol)

Molecular formula $C_{26}H_{40}N_2O_1S_2$

Molecular weight 556 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.43 (s, 1H), 7.37-7.35 (m, 3H), 7.33-7.26 (m, 3H), 7.25 (s, 1H), 5.95 (s, 1H), 5.40 (d, *J* = 18 Hz, 1H), 5.22 (d, *J* = 18 Hz, 1H), 4.21-4.17 (m, 2H), 3.91 (s, 3H), 3.49-3.41 (m, 2H), 3.32-3.17 (m, 2H), 1.55-1.51 (m, 2H), 1.21-1.06 (m, 10H), 1.03 (t, *J* = 7.0 Hz, 3H), 0.80 (t, *J* = 6.8 Hz, 3H)

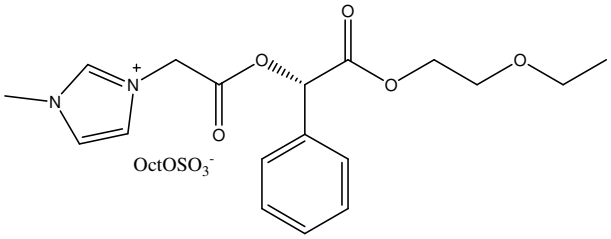
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 167.97, 165.88, 139.11, 132.30, 129.74, 128.93, 127.84, 123.58, 122.98, 76.21, 68.22, 67.85, 66.56, 65.05, 49.87, 36.65, 31.82, 29.40, 29.32, 29.25, 25.80, 22.66, 15.04, 14.13

IR (thin film on salt plate) (cm^{-1}) 3160, 3116, 2953, 2927, 2857, 1749, 1566, 1559, 1539, 1495, 1457, 1402, 1203, 1177

MS *m/z*, 347.2 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.1 $[OctOSO_3^-]$

$[\alpha]_D^{20}$ -35.7º (0.4 c, Acetone)

_S_ - 3-Methyl-1-(ethoxyethylmandelylcarbonylmethyl)imidazolium $OctOSO_3$ (217k)



Brown viscous liquid

The title compound was prepared from *S* - 3-methyl-1-(ethoxy ethyl mandelyl carbonyl methyl) imidazolium bromide **213k** (2.30 mmol, 1.00 g) and sodium octyl sulfate (2.40 mmol, 0.56 g) according to the general procedure in 71 % yield (0.92 g, 1.65 mmol)

Molecular formula $C_{26}H_{40}N_2O_1S_2$

Molecular weight 556 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.36 (s, 1H), 7.39-7.20 (m, 7H), 5.95 (s, 1H), 5.40 (d, *J* = 18 Hz, 1H), 5.23 (d, *J* = 18 Hz, 1H), 4.26-4.16 (m, 2H), 3.91 (s, 3H), 3.59-3.45 (m, 2H), 3.36-3.29 (m, 2H), 1.58-1.51 (m, 2H), 1.08-1.01 (m, 10H), 1.03 (t, *J* = 7.0 Hz, 3H), 0.80 (t, *J* = 6.8 Hz, 3H)

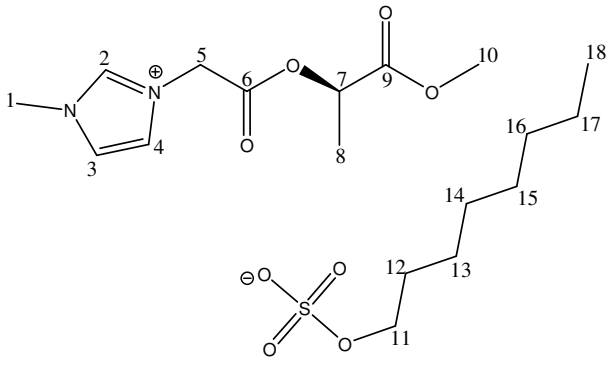
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.68, 167.98, 165.94, 138.94, 132.35, 129.72, 128.92, 128.55, 128.43, 127.84, 126.58, 123.63, 76.18, 72.82, 68.18, 66.63, 65.23, 49.85, 36.62, 31.82, 29.32, 25.80, 22.66, 15.04

IR (thin film on salt plate) (cm^{-1}) 2955, 2927, 2858, 1751, 1559, 1539, 1495, 1452, 1204, 1171

MS *m/z*, 347.2 $[M\text{-}OctOSO_3^-]^+$; MS: *m/z*, 209.1 $[OctOSO_3^-]$

$[\alpha]_D^{20}$ +36.1° (0.4 c, Acetone)

_R_ - 3-Methyl-1-(methyllactylcarbonylmethyl)imidazolium $OctOSO_3$ (218a)



Brown viscous liquid

The title compound was prepared from *R* - 3-methyl-1-(methyl lactyl carbonyl methyl) imidazolium bromide **214a** (2.50 mmol, 0.77 g) and sodium octyl sulfate (2.60 mmol, 0.60 g) according to the general procedure in 94 % yield (1.02 g, 2.33 mmol)

Molecular formula $C_{18}H_{32}N_2O_8S$

Molecular weight 436 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.28 (s, 1H, *H2*), 7.53 (t, *J* = 1.6 Hz, 1H, *H4*), 7.51 (t, *J* = 1.6 Hz, 1H, *H3*), 5.33 (d, *J* = 18.0 Hz, 1H, *H5*), 5.20 (d, *J* = 18.0 Hz, 1H, *H5*), 5.14 (q, *J* = 7.2 Hz, 1H, *H7*), 3.92 (m 5H, *H's 11 and 10*), 3.67 (s, 3H, *H1*), 1.60 (tt, *J* = 7.2, 7.1 Hz, 2H, *H12*), 1.47 (d, *J* = 7.1 Hz, 3H, *H8*), 1.27 (m, 10H, *H's 13-17*), 0.81 (t, *J* = 6.9 Hz, 3H, *H18*)

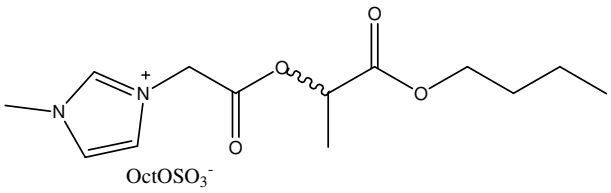
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 170.32 (*C*OO), 166.02 (*C*OO), 138.48 (N*C*HN), 123.87 (N*C*H_2), 123.46 (N*C*H_2), 70.49 (O*C*H_3), 67.72 (*C*H), 52.59 (O*C*H_2), 49.61 (N*C*H_2), 36.43 (N*C*H_3), 31.74 (*C*H_2), 29.44 (*C*H_2), 29.28 (*C*H_2), 29.18 (*C*H_2), 25.81 (*C*H_2), 22.57 (*C*H_2), 16.73 (C*C*H_3), 14.04 (*C*H_3)

IR (thin film on salt plate) (cm^{-1}) 3160, 3118, 2958, 2927, 2859, 1751, 1567, 1559, 1539, 1495, 1452, 1376, 1217, 1133

MS *m/z*, 227.1 [M-OctOSO_3^-]$^+$; MS: *m/z*, 209.1 [OctOSO_3^-]

$[\alpha]_D^{20}$ -30.7º (0.4 c, Chloroform)

RS - 3-Methyl-1-(butyllactylcarbonylmethyl)imidazolium OctOSO_3 (218g)



Pale brown grease

The title compound was prepared from *RS* - 3-methyl-1-(butyl lactyl carbonyl methyl) imidazolium bromide **214g** (2.55 mmol, 0.89 g) and sodium octyl sulfate (2.65 mmol, 0.61 g) according to the general procedure in 90 % yield (1.10 g, 2.30 mmol)

Molecular formula $C_{21}H_{38}N_2O_8S$

Molecular weight 478 g/mol

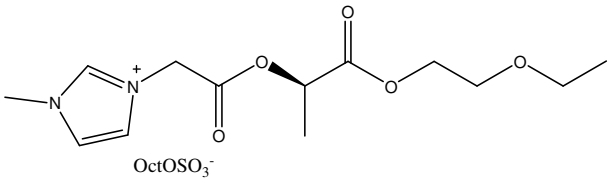
^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.37 (s, 1H), 7.43 (t, *J* = 1.6 Hz, 1H), 7.40 (t, *J* = 1.6 Hz, 1H), 5.39 (d, *J* = 18.0 Hz, 1H), 5.14-5.11 (m, 2H), 4.10-4.07 (m, 2H), 3.95-3.92 (m 5H), 1.62-1.57 (m, 4H), 1.48 (d, *J* = 7.0 Hz, 3H), 1.32 (m, 12H), 0.88 (t, J= 7.4 Hz, 3H), 0.82 (t, *J* = 7.0 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.93, 165.91, 138.83, 123.67, 123.25, 70.66, 67.90, 65.60, 49.78, 36.58 31.82, 30.44, 29.49, 29.35, 29.25, 25.86, 22.65, 18.97, 16.81, 14.11, 13.65

IR (thin film on salt plate) (cm^{-1}) 3160, 3115, 2958, 2928, 2859, 1751, 1581, 1569, 1559, 1495, 1457, 1377, 1209, 1131

MS *m/z*, 269.2 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

_R_ - 3-Methyl-1-(ethoxyethyllactylcarbonylmethyl)imidazolium $OctOSO_3$ (218k)



Pale brown grease

The title compound was prepared from *R* - 3-methyl-1-(ethoxy ethyl lactyl carbonyl methyl) imidazolium bromide **214k** (2.00 mmol, 0.73 g) and sodium octyl sulfate (2.10 mmol, 0.49 g) according to the general procedure in 90 % yield (0.89 g, 1.80 mmol)

Molecular formula $C_{21}H_{38}N_2O_9S$

Molecular weight 494 g/mol

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.46 (s, 1H), 7.42 (t, *J* = 1.6 Hz, 1H), 7.33 (t, *J* = 1.6 Hz, 1H), 5.41 (d, *J* = 17.6 Hz, 1H), 5.15 (m, 2H), 4.27 (m, 2H), 3.96 (m 5H), 3.58 (t, *J* = 4.7 Hz, 2H), 3.48 (t, *J* = 7.0 Hz, 2H), 1.63 (tt, *J* = 7.4, 7.0 Hz, 2H), 1.51 (d, *J* = 7.1 Hz, 3H), 1.23-1.14 (m, 10H), 1.14 (t, *J* = 7.0 Hz, 3H), 0.82 (t, *J* = 6.9 Hz, 3H)

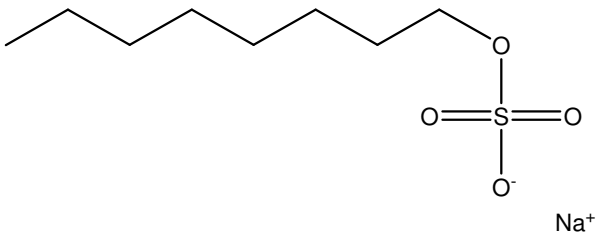
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 169.89, 165.90, 138.92, 123.68, 123.12, 70.66, 68.11, 67.96, 66.61, 64.69, 49.83, 36.64, 31.82, 29.45, 29.34, 29.26, 25.84, 22.66, 16.76, 15.11, 14.12

IR (thin film on salt plate) (cm^{-1}) 3161, 3118, 2957, 2927, 2859, 1749, 1568, 1559, 1539, 1495, 1456, 1377, 1217

MS *m/z*, 285.1 [M-$OctOSO_3^-$]$^+$; MS: *m/z*, 209.1 [$OctOSO_3^-$]

$[\alpha]_D^{20}$ -27.8º (0.5 c, Chloroform)

Synthesis of sodium octyl sulphate (196)



To a stirred solution of 1-octanol (50.0 mmol, 6.50 g) in DCM was added in one portion chlorosulfonic acid (50.1 mmol, 5.89 g). The mixture was stirred at RT for 30 minutes then slowly neutralised with sodium bicarbonate. The DCM was then evaporated *via* rotary evaporation and methanol was added to the residue. The residue was filtered thru a short silica plug. The filtrate was evaporated to dryness to give sodium octyl sulfate (white powder) in 99 % yield (11.47 g, 49.44 mmol).

Molecular formula $C_8H_{17}NaO_4S$

Molecular weight 232 g/mol

^{1}H NMR (400 MHz, D_2O) δ ppm 3.99 (t, J = 6.6 Hz, 2H), 1.63-1.59 (m, 2H), 1.31-1.22 (m, 10H), 0.81-0.80 (m, 3H)

^{13}C NMR (100 MHz, D_2O) δ ppm 69.64, 30.97, 30.13, 28.22, 28.10, 24.73, 21.92, 13.31

Chapter 4 experimental

***Trans*-stilbene (220)**

Hydrogenation reaction in [NTf_2] IL

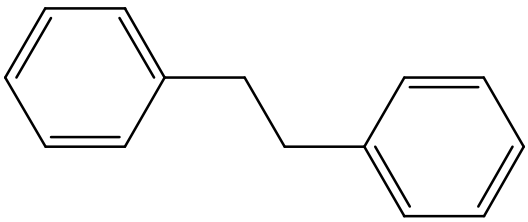
10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by *trans*-stilbene (0.72 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 100 % (0.72 g). Quantitative analysis of the reaction products was carried out by measuring the integration ratio of the peaks from the crude NMR spectrum. 1,2-diphenylethane was obtained in 99 % yield (0.72 g, 3.96 mmol).

Recycle procedure

Following extraction of the products from the IL, the IL (containing the catalyst) was dried *via* rotary evaporation and analysed by ^{1}H NMR. Following confirmation that the IL was substrate/product-free and had not degraded, fresh substrate was then added to the system and the reactions repeated as described.

Hydrogenation reaction in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by *trans*-stilbene (0.72 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon, and due to the viscous nature of the octyl sulfate IL, the progress of the reaction could not be monitored by ^{1}H NMR. Upon termination of the reaction, the product was distilled from the IL using vacuum distillation at 200 °C. It was observed that during this intensive heating procedure, that degraded IL was also distilled. Column chromatography was performed (80:20, Hexane:DCM) to separate the degraded IL from the product. The mass recovery following distillation and column chromatography was 43 % (0.31 g). 1,2-diphenylethane was obtained in 42 % yield (0.31 g, 1.70 mmol).



1,2-diphenylethane

229

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.33-7.28 (m, 4H), 7.24-7.20 (m, 6H), 2.95 (s, 4H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 141.87, 128.55, 128.44, 126.06, 38.06

Data consistent with literature[1]

***Trans*-cinnamaldehyde (94)**

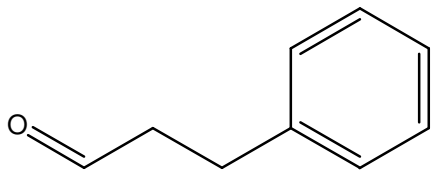
Hydrogenation reaction in [NTf_2] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by *trans*-

cinnamaldehyde (0.53 g, 4.02 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 100 % (0.53 g). Quantitative analysis of the reaction products was carried out by measuring the integration ratio of the peaks from the crude NMR spectrum (hydrocinnamadehyde:3-phenyl propanol, 1:0.15). These values were then verified by purification of the product by column chromatography (hexane:ethyl acetate, 70:30) to give hydrocinnamaldehyde in 82 % yield (0.44 g, 3.28 mmol) and 3-phenyl propanol in 12 % yield (0.065 g, 0.48 mmol).

Hydrogenation reaction in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by *trans*-cinnamaldehyde (0.53 g, 4.02 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon. Upon termination of the reaction, vacuum distillation was used to separate the products from the IL and the catalyst. The mass recovery after extraction from the IL was 42 % (0.22 g). Quantitative analysis of the reaction products was carried out by measuring the integration ratio of the peaks from the crude NMR spectrum (*trans*-cinnamaldehyde:hydrocinnamadehyde, 1:0.33). These values were then verified by purification of the product by column chromatography (hexane:ethyl acetate, 70:30) to give back trans-cinnamaldehyde in 32 % yield (0.17 g, 1,29 mmol) and hydrocinnamaldehyde in 9 % yield (0.05 g, 0.37 mmol).



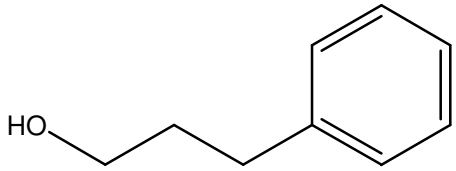
hydrocinnamaldehyde

95

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.85 (t, *J* = 1.4 Hz, 1H), 7.35-7.31 (m, 2H), 7.26-7.22 (m, 3H), 2.99 (t, *J* = 7.4 Hz, 2H), 2.83-2.79 (m, 2H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 203.49, 141.32, 128.01, 127.99, 127.89, 40.33, 29.63

Data consistent with literature[2]



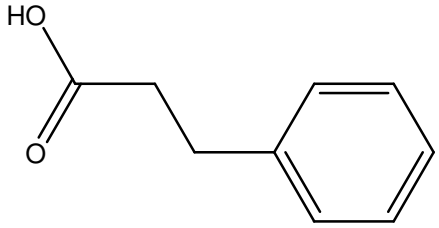
3-phenylpropan-1-ol

97

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.23-7.18 (m, 2H), 7.14-7.10 (m, 3H), 3.62 (t, *J* = 6.6 Hz, 2H), 2.62 (t, *J* = 7.4 Hz, 2H), 1.82 (tt, *J* = 6.6, 7.4 Hz, 2H), 1.55 (br s, 1H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 141.20, 129.01, 128.93, 126.50, 62.33, 34.30, 33.67

Data consistent with literature[3]



3-phenylpropanoic acid

231

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 11.00 (br s, 1H), 7.24-7.20 (m, 2H), 7.14-7.12 (, 3H), 2.90 (t, *J* = 7.8 Hz, 2H), 2.63 (t, *J* = 7.8 Hz, 2H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 178.39, 147.87, 128.58, 128.29, 126.40, 35.50, 28.23

Data consistent with literature[4]

***Trans*-cinnamic acid (221)**

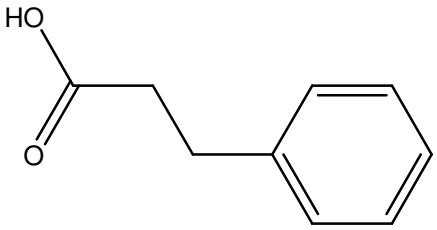
Hydrogenation reaction in [NTf_2] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by trans-cinnamic acid (0.59 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the

reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 98 % (0.58 g). 3-phenylpropanoic acid was obtained in 97 % yield (0.58 g, 3.87 mmol).

Hydrogenation in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by trans-cinnamic acid (0.59 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon. Vacuum distillation was attempted to recover the product from the IL, however the only material distilled was the starting alcohol to synthesise the IL (The IL had degraded at a temperature of 200 °C). The IL/catalyst and product were therefore filtered through a short plug of silica to separate the product from the mixture. The mass recovery after extraction from the IL was 15 % (0.09 g). 3-phenylpropanoic acid was obtained in 15 % yield (0.09 g, 0.60 mmol).



3-phenylpropanoic acid

231

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 11.00 (br s, 1H), 7.23-7.19 (m, 2H), 7.14-7.11 (m, 3H), 2.89 (t, *J* = 7.8 Hz, 2H), 2.69 (t, *J* = 7.8 Hz, 2H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 178.97, 140.16, 128.59, 128.29, 126.40, 35.59, 30.58

Data consistent with literature[5]

Methyl cinnamate (222)

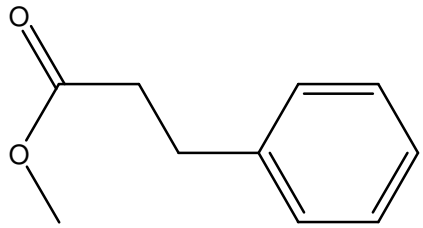
Hydrogenation reaction in [NTf_2] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by methyl cinnamate (0.65 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to

the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 100 % (0.65 g). Methyl 3-phenylpropanoate was obtained in 98 % yield (0.65 g, 3.96 mmol).

Hydrogenation reaction in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by methyl cinnamate (0.65 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon. Upon termination of the reaction, the products were extracted using vacuum distillation (~150 °C). Degraded IL (the starting alcohol) was also obtained in the distillate, therefore column chromatography (Hexane:Ethyl Acetate, 90:10) was used to separate this impurity from the desired product. The mass recovery was 69 % (0.45 g). Methyl 3-phenylpropanoate was obtained in 68 % yield (0.45 g, 2.74 mmol).



methyl 3-phenylpropanoate

232

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.23-7.19 (m, 2H), 7.14-7.10 (m, 3H), 3.59 (s, 3H), 2.89 (t, J = 7.9 Hz, 2H), 2.57 (t, J = 7.9 Hz, 2H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.40, 140.52, 128.53, 128.30, 126.29, 51.67, 37.44, 30.95

Data consistent with literature[6]

Ethyl *trans*-cinnamate (223)

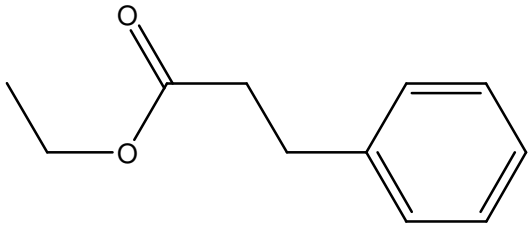
Hydrogenation reaction in [NTf_2] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by ethyl trans-

cinnamate (0.70 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 99 % (0.69 g). Ethyl 3-phenylpropanoate was obtained in 97 % yield (0.69 g, 3.88 mmol).

Hydrogenation in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by ethyl trans-cinnamate (0.70 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon. Upon termination of the reaction, the products were extracted using vacuum distillation (~125 °C). Degraded IL (starting alcohol) was obtained in the distillate, and therefore column chromatography (Hexane:Ethyl Acetate, 20:80) was used to separate it from the product. The mass recovery was 76 % (0.53 g). Ethyl 3-phenylpropanoate was obtained in 74% yield (0.53 g, 2.98 mmol).



ethyl 3-phenylpropanoate

233

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.22-7.20 (m, 2H), 7.15-7.12 (m, 3H), 4.09 (q, *J* = 7.2 Hz, 2H), 2.90 (t, *J* = 7.9 Hz, 2H), 2.57 (t, *J* = 7.9 Hz, 2H), 1.18 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 172.97, 140.34, 128.52, 126.52, 60.46, 38.03, 36.01, 14.27

Data consistent with literature[7]

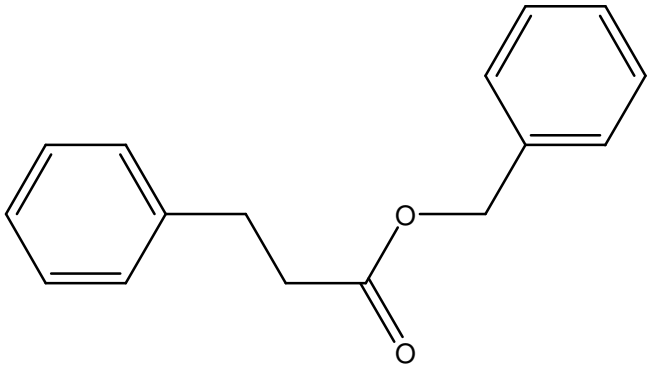
Benzyl cinnamate (224)

Hydrogenation reaction in [NTf_2] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by benzyl cinnamate (0.95 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). Column chromatography (Hexane:Ethyl acetate, 1:4) was used to separate the resulting product, namely cinnamic acid and benzyl 3-phenylpropanoate. The mass recovery after extraction from the IL was 45 % (0.43 g). 3-phenylpropanoic acid was obtained in 72 % yield (0.43 g, 2.87 mmol).

Hydrogenation in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by benzyl cinnamate (0.95 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon. Upon termination of the reaction, vacuum distillation was attempted as the method for separation of the product from the IL mixture. It was however not viable to separate the product from the IL in this way therefore the mixture was filtered through a short plug of silica. The mass recovery was 56 % (0.53 g). Benzyl 3-phenylpropanoate was obtained in 55 % yield (0.53 g, 2.21 mmol).



benzyl 3-phenylpropanoate

234

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.29-7.09 (m, 10H), 5.03 (s, 2H), 2.91 (t, *J* = 7.8 Hz, 2H), 2.62 (t, *J* = 7.8 Hz, 2H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 172.80, 140.44, 135.94, 128.60, 128.56, 128.46, 128.36, 128.27, 126.33, 66.34, 35.21, 30.74

Data consistent with literature[8]

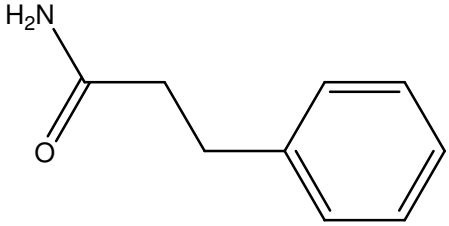
Cinnamamide (226)

Hydrogenation reaction in [NTf_2] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by cinnamamide (0.59 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 100 % (0.59 g). 3-phenylpropanamide was obtained in 98 % yield (0.59 g, 4.00 mmol).

Hydrogenation in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by cinnamamide (0.59 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon. Upon termination of the reaction, the products were extracted using vacuum distillation (~190 °C). The mass recovery after extraction from the IL was 69 % (0.41 g). 3-phenylpropanamide was obtained in 68 % yield (0.41 g, 2.75 mmol).



3-phenylpropanamide

237

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.25-7.21 (m, 2H), 7.15-7.12 (m, 3H), 5.52 (br s, 1H), 5.34 (br s, 1H), 2.92 (t, *J* = 7.7 Hz, 2H), 2.48 (t, *J* = 7.7 Hz, 2H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 174.60, 140.64, 128.60, 128.34, 126.35, 37.54, 31.39

Data consistent with literature[6]

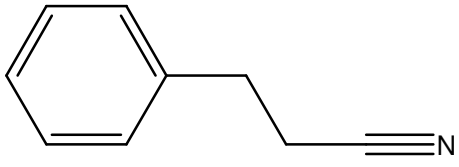
Cinnamamonitrile (225)

Hydrogenation reaction in [NTf_2] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by cinnamonitrile (0.52 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 100 % (0.52 g). 3-phenylpropanenitrile was obtained in 100 % yield (0.52 g, 4.00 mmol).

Hydrogenation in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by cinnamonitrile (0.52 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon. Upon termination of the reaction, the products were extracted using vacuum distillation. The mass recovery after extraction from the IL was 35 % (0.18 g). 3-phenylpropanenitrile was obtained in 35 % yield (0.18 g, 1.37 mmol).



3-phenylpropanenitrile

238

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.40-7.26 (m, 5H), 2.99 (t, *J* = 7.5 Hz, 2H), 2.65 (t, *J* = 7.5 Hz, 2H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 138.11, 128.72, 128.47, 127.48, 119.24, 30.99, 19.38

Data consistent with literature[6]

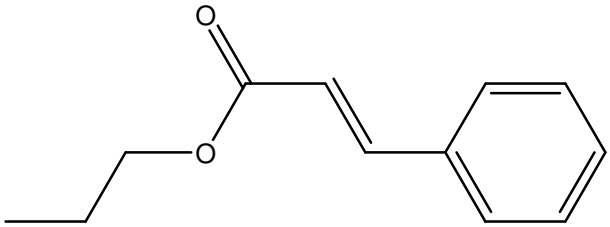
Allyl cinnamate (227)

Hydrogenation reaction in [NTf_2] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by allyl cinnamate (0.75 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 100 % (0.75 g). The products were identified quantitatively by examination of the ^{1}H NMR spectrum (propyl cinnamate:propyl 3-phenylpropanoate, 1:0.19). The mass recovery after extraction from the IL was 100 % (0.75 g). Column chromatography was used for the purification of the obtained products (10:90, Hexane:DCM). Propyl cinnamate was obtained in 80 % yield (0.61 g, 3.20 mmol) and propyl 3-phenylpropanoate was obtained in 12 % yield (0.09 g, 0.47 mmol).

Hydrogenation in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by allyl cinnamate (0.75 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon. Upon termination of the reaction, the products were extracted using vacuum distillation (~ 180 °C). The mass recovery after extraction from the IL was 67 % (0.50 g). Propyl 3-phenylpropanoate was obtained in 65 % yield (0.50 g, 2.60 mmol).



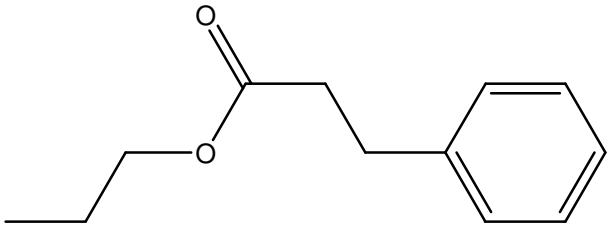
propyl cinnamate

236

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.74 (d, *J* = 16 Hz, 1H), 7.56-7.54 (m, 2H), 7.42-7.38 (m, 3H), 6.50 (d, *J* = 16 Hz, 1H), 4.21 (t, *J* = 6.7 Hz, 2H), 1.79 (tq, *J* = 6.7, 7.8 Hz, 2H), 1.04 (t, *J* = 7.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 166.25, 143.20, 131.70, 129.29, 129.26, 129.00, 118.03, 61.52, 22.83, 17.01

Data consistent with literature[9]



propyl 3-phenylpropanoate

235

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.34-7.30 (m, 2H), 7.25-7.22 (m, 3H), 4.09 (t, *J* = 7.0 Hz, 2H), 3.02 (t, *J* = 7.8 Hz, 2H), 2.69 (t, *J* = 7.8 Hz, 2H), 1.71 (tq, *J* = 7.0, 7.3 Hz, 2H), 0.97 (t, *J* = 7.3 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 173.06, 140.60, 128.50, 128.32, 126.25, 66.29, 37.43, 31.03, 21.98, 10.40

Data consistent with literature[10]

Vinyl cinnamate (228)

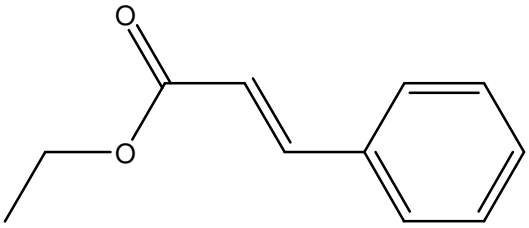
Hydrogenation reaction in [NTf_2] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by vinyl cinnamate (0.70 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR at 5, 24 and 48 hour intervals. Upon termination of the reaction, the products were

extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 100 % (0.70 g) Ethyl 3-phenylpropanoate was obtained in 99 % yield (0.70 g, 3.93 mmol).

Hydrogenation in [$OctOSO_3$] IL

10 % Pd/C (5.0 mg, 0.12 mol %) was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by vinyl cinnamate (0.70 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 80 °C. Hydrogen was then introduced to the reaction via a balloon. Upon termination of the reaction, the products were extracted using vacuum distillation. The mass recovery after extraction from the IL was 67 % (0.47 g). Ethyl 3-phenylpropanoate was obtained in 66 % yield (0.47 g, 2.64 mmol).



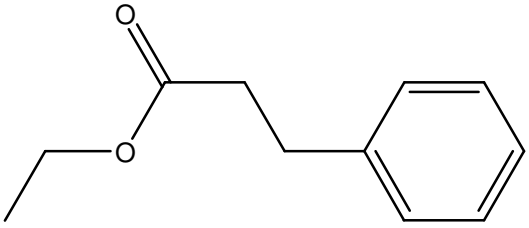
ethyl cinnamate

223

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.73 (d, *J* = 16 Hz, 1H), 7.55-7.52 (m, 2H), 7.42-7.38 (m, 3H), 6.48 (d, *J* = 16 Hz, 1H), 4.31 (q, *J* = 7.1 Hz, 2H), 1.38 (t, *J* = 7.1 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 166.99, 144.93, 134.74, 130.55, 128.58, 128.06, 118.64, 60.50, 14.53

Data consistent with literature[9]



ethyl 3-phenylpropanoate

233

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.34-7.30 (m, 2H), 7.25-7.23 (m, 3H), 4.19 (q, *J* = 7.2 Hz, 2H), 3.01 (t, *J* = 7.8 Hz, 2H), 2.67 (t, *J* = 7.8 Hz, 2H), 1.29 (t, *J* = 7.2 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 172.92, 140.62, 128.51, 128.34, 126.26, 60.43, 35.98, 31.01, 14.24

Data consistent with literature[7]

Experimental Chapter 5

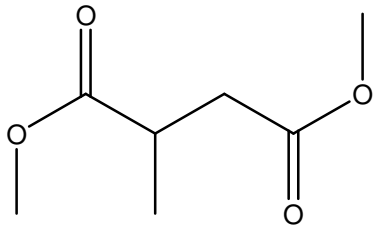
Dimethyl itaconate (144)

Hydrogenation reaction in [NTf_2] IL

The catalyst [(10 % Pd/C, 5.0 mg, 0.12 mol %), (Tris(triphenylphosphine)rhodium(I) chloride, 0.05 g, 1.35 mol %) (bis(norbornadiene)rhodium(I) BF_4, Taniaphos, 0.003 mmol, 0.75 mol %)] was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by dimethyl itaconate (0.63 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 100 % (0.63 g). Dimethyl 2-methylsuccinate was obtained in 98 % yield (0.63 g, 3.94 mmol).

Recycle procedure

Following extraction of the products from the IL, the IL (containing the catalyst) was dried *via* rotary evaporation and analysed by ^{1}H NMR. Following confirmation that the IL was substrate/product-free and had not degraded, fresh substrate was then added to the system and the reactions repeated as described.



dimethyl 2-methylsuccinate

157

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 3.63 (s, 3H), 3.61 (s, 3H), 2.88-2.83 (m, 1H), 2.70 (dd, *J* = 8.2, 8.2 Hz, 1H), 2.37 (dd, *J* = 6.0, 6.0 Hz, 1H), 1.16 (d, *J* = 7.2 Hz, 3H)

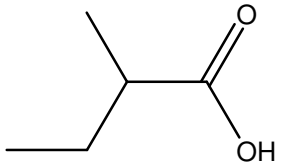
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 175.98, 172.27, 51.89, 51.68, 37.15, 35.64, 16.96

Data consistent with literature[11]

Tiglic acid (239)

Hydrogenation reaction in [NTf_2] IL

The catalyst [(10 % Pd/C, 5.0 mg, 0.12 mol %), (Tris(triphenylphosphine)rhodium(I) chloride, 0.05 g, 1.35 mol %), (PtO_2, 5.0 mg, 0.55 mol %)] was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by tiglic acid (0.40 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 100 % (0.40 g). 2-Methylbutanoic acid was obtained in 98 % yield (0.40 g, 3.92 mmol).



2-methylbutanoic acid

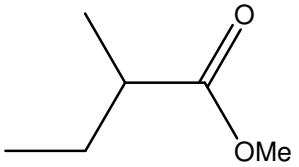
244

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 11.58 (br s, 1H), 2.35 (q, *J* = 7.2 Hz, 1H), 1.68-1.61 (m, 1H), 1.46-1.40 (m, 1H), 1.11 (d, *J* = 7.2 Hz, 3H), 0.89 (t, *J* = 7.4 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 183.71, 40.74, 26.51, 16.32, 11.51

Data consistent with literature[12]

Formation of methyl 2-methylbutanoate



methyl 2-methylbutanoate

247

To a stirred solution of methanol (1 mL) and toluene (2 mL) was added TMS diazomethane in diethylether (0.98 mL, 1.96 mmol). The mixture was allowed to stir for 1 hour, after which 2-methylbutanoic acid (0.199 g, 1.96 mmol) in methanol (1 mL) was added. Upon complete dissipation of the yellow colour, the mixture was washed with 10 % acetic acid (2 x 3 mL) and extracted with diethyl ether (2 x 3 mL).

The extract was then washed with sodium bicarbonate (2 x 3 mL) and dried on the high vacuum to give a pale yellow oil at RT in 82 % yield (0.190 g, 1.64 mmol).

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 3.60 (s, 3H), 2.33 (q, *J* = 7.2 Hz, 1H), 1.66-1.59 (m, 1H), 1.45-1.40 (m, 1H), 1.09 (d, *J* = 7.2 Hz, 3H), 0.90 (t, *J* = 7.2 Hz, 3H)

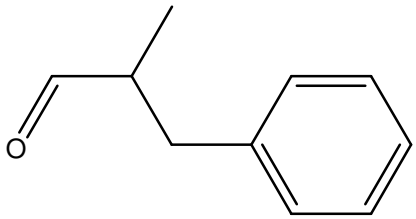
^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 180.22, 51.34, 38.78, 24.22, 15.98, 11.01

Data consistent with literature[13]

α-Methyl-*trans*-cinnamaldehyde (240)

Hydrogenation reaction in [NTf_2] IL

The catalyst [(10 % Pd/C, 5.0 mg, 0.12 mol %), (Tris(triphenylphosphine)rhodium(I) chloride, 0.05 g, 1.35 mol %), (PtO_2, 5.0 mg, 0.55 mol %)] was weighed into a dry 2-neck round bottom flask. The pre-dried IL (2.0 mL) was then added to the flask, followed by α-methyl-*trans*-cinnamaldehyde (0.58 g, 4.00 mmol) and 3 N_2/vacuum cycles were performed. The reaction mixture was stirred for 10 minutes or until reaching 55 °C. Hydrogen was then introduced to the reaction via a balloon, and the progress of the reaction was monitored by ^{1}H NMR. Upon termination of the reaction, the products were extracted using hexane (10 x 3 mL). The mass recovery after extraction from the IL was 98 % (0.57 g). Quantitative analysis of the reaction products was carried out by measuring the integration ratio of the peaks from the crude ^{1}H NMR spectrum (α-methyl-*trans*-cinnamaldehyde: 2-methyl-3-phenylpropanal: 2-methyl-3-phenylpropan-1-ol, 1:0.85:0.42). These values were then verified by purification of the product by column chromatography (DCM:hexane, 50:50) to give α-methyl-*trans*-cinnamaldehyde in 44 % yield (0.25 g, 1.71 mmol), 2-methyl-3-phenylpropanal in 35 % yield (0.20 g, 1.35 mmol) and 2-methyl-3-phenylpropan-1-ol in 18 % yield (0.10 g, 6.67 mmol).



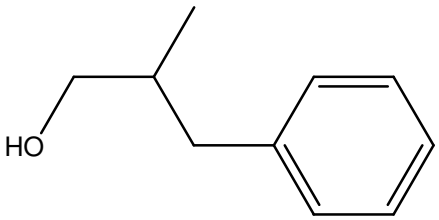
2-methyl-3-phenylpropanal

245

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 9.75 (d, *J* = 1.6 Hz, 1H), 7.35-7.20 (m, 5H), 3.15 (dd, *J* = 5.6, 5.6 Hz, 1H), 2.73-2.61 (m, 2H), 1.13 (d, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 182.39, 139.03, 128.84, 128.45, 126.45, 41.24, 39.30, 16.51

Data consistent with literature[14]



2-methyl-3-phenylpropan-1-ol

246

^{1}H NMR (400 MHz, $CDCl_3$) δ ppm 7.26-7.18 (m, 2H), 7.14-7.09 (m, 3H), 3.48-3.37 (m, 2H), 2.71 (dd, *J* = 6.4, 6.4 Hz, 1H), 2.38 (dd, *J* = 8.0, 8.0 Hz, 1H), 1.90-1.83 (m, 1H), 1.46 (br s, 1H), 0.85 (d, *J* = 6.8 Hz, 3H)

^{13}C NMR (100 MHz, $CDCl_3$) δ ppm 141.21, 128.24, 128.03, 126.86, 68.25, 40.00, 38.29, 16.78

Data consistent with literature[14]

Note: A discussion of enantiomeric excess determination is given in section 5.5.

Bibliography

1 (a) Sigma Aldrich, NMR 14330 (b) Beil., **5**, IV, 1868

2 (a) Sigma Aldrich, NMR 56660; (b) Beil., **7**, IV, 692

3 (a) Sigma Aldrich, NMR 140856; (b) Beil., **6**, IV, 3198

4 (a) Sigma Aldrich, NMR W288918; (b) Beil., **9**, III, 2382

5 (a) Sigma Aldrich, NMR W288918; (b) Beil., **9**, III, 2382

6 V. Kumar, A. Sharma and A. Sinha, *Helvatic Chimica Acta,* 2006, **89**, 483.

7 S. Chandrasekhar, G. Reddy, C. Nagesh and C. Reddy, *Tetrahedron Lett.,* 2007, **48**, 1269.

8 P. Black, G. Cami-Kobeci, M. Edwards, P. Slatford, M. Whittlesey and J. williams, *Org. Biomol. Chem.,* 2006, **4**, 116.

9 S. Yan-mei, L. Jing, Z. Ping, S. Zhi-guang, L. Ye-zhi and H. Hua-min, *Chem. Res. Chinese U.,* 2007, **23**, 669.

10 S. Kiyooka, Y. Wada, M. Ueno, T. Yokoyama and R. Yokoyama, *Tetrahedron,* 2007, **63**, 12695.

11 (a) Sigma Aldrich, NMR 178799 (b) Beil., **2**, III, 1696

12 M. Kawashima, T. Sato and T. Fujisawa, *Tetrahedron,* 1989, **45**, 403.

13 Z. Jedlinski, A. Misiolek and P. Kurcok, *J. Org. Chem.,* 1989, **54**, 1500.

14 A. Myers, B. Yang and H. Chen, *Organic Synthesis,* 2004, **77**, 29.

Appendix B

Table of figures

Appendix C

X-Ray Crystallographic Data

186a

Crystal data and structure refinement for **186a**

Identification code	**186a**	
Empirical formula	$C_{14}\ H_{25}\ N_2\ O_4\ Br$	
Molecular formula	$[C_{14}\ H_{25}\ N_2\ O_4]^+[Br]^-$	
Formula weight	365.27	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	$P2_1/c$ (#14)	
Unit cell dimensions	a = 10.584(2) Å	α = 90°.
	b = 11.258(2) Å	β = 90.776(4)°.
	c = 28.849(6) Å	γ = 90°.
Volume	3437.2(12) $Å^3$	
Z	8	
Density (calculated)	1.412 Mg/m^3	
Absorption coefficient	2.408 mm^{-1}	
F(000)	1520	
Crystal size	1.00 x 0.60 x 0.20 mm^3	
Theta range for data collection	1.92 to 23.00°.	
Index ranges	–11<=h<=11, –12<=k<=12, –31<=l<=31	
Reflections collected	21607	
Independent reflections	4766 [R(int) = 0.0493]	
Completeness to theta = 23.00°	99.8 %	
Absorption correction	None	
Max. and min. transmission	0.6445 and 0.4335	
Refinement method	Full–matrix least–squares on F^2	
Data / restraints / parameters	4766 / 86 / 383	
Goodness–of–fit on F^2	1.132	
Final R indices [I>2sigma(I)]	R1 = 0.0670, wR2 = 0.1597	

R indices (all data)	R1 = 0.0791, wR2 = 0.1647
Largest diff. peak and hole	1.489 and –2.352 e.Å^{-3}

Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters (Å^{2}x 10^3) for **186a**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Atom	x	y	z	U(eq)
Br(1)	2387(1)	7881(1)	1735(1)	18(1)
Br(2)	7365(1)	3662(1)	6733(1)	18(1)
C(1)	–1605(7)	586(8)	6479(3)	25(2)
N(1)	–680(5)	473(5)	6859(2)	15(1)
C(2)	–611(6)	1141(7)	7236(3)	14(2)
N(2)	315(5)	705(6)	7512(2)	16(1)
C(3)	231(7)	–408(7)	6890(3)	17(2)
C(4)	843(7)	–263(7)	7297(3)	18(2)
C(5)	748(7)	1232(7)	7946(3)	17(2)
C(6)	2105(7)	1672(7)	7909(3)	17(2)
O(1)	2737(5)	1587(5)	7570(2)	20(1)
O(2)	2478(4)	2106(4)	8317(2)	16(1)
C(7)	3808(7)	2450(8)	8342(3)	24(2)
C(8)	4172(7)	2661(7)	8836(3)	24(2)
O(3)	3746(5)	3790(5)	8979(2)	21(1)
C(9)	3973(8)	3994(7)	9455(3)	25(2)
C(10)	3656(8)	5264(8)	9571(3)	28(2)
O(4)	4629(5)	6029(5)	9414(2)	26(1)
C(11)	4290(8)	7256(8)	9447(3)	28(2)
C(12)	5440(8)	8017(8)	9367(3)	27(2)
C(13)	5125(8)	9337(8)	9369(3)	30(2)
C(14)	6308(8)	10109(8)	9351(3)	33(2)
C(15)	6565(7)	–158(7)	3556(3)	18(2)
N(3)	5688(5)	–310(5)	3165(2)	15(1)

C(16)	5609(6)	349(7)	2789(3)	15(2)
N(4)	4712(5)	–85(5)	2506(2)	14(1)
C(17)	4829(6)	–1231(7)	3122(3)	18(2)
C(18)	4226(7)	–1087(7)	2715(3)	18(2)
C(19)	4265(7)	416(7)	2074(3)	17(2)
C(20)	2919(6)	882(6)	2123(3)	13(2)
O(5)	2317(4)	811(4)	2474(2)	17(1)
O(6)	2524(4)	1357(5)	1724(2)	19(1)
C(21)	1196(7)	1694(7)	1715(3)	20(2)
C(22)	766(7)	1878(7)	1227(3)	21(2)
O(7)	1214(5)	2996(5)	1067(2)	20(1)
C(23)	878(7)	3212(7)	597(3)	22(2)
C(24)	1264(7)	4424(7)	458(3)	23(2)
O(8)	437(5)	5274(5)	662(2)	26(1)
C(25)	797(7)	6470(7)	570(3)	24(2)
C(26)	–274(8)	7295(7)	683(3)	26(2)
C(27)	18(9)	8587(8)	572(3)	34(2)
C(28)	–1134(9)	9399(8)	610(3)	39(2)

191a

Crystal data and structure refinement for **191a**

Identification code	**191a**	
Empirical formula	C_{12} H_{21} N_2 O_4 Br	
Molecular formula	$[C_{12}$ H_{21} N_2 $O_4]^+[Br]^-$	
Formula weight	337.22	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	$P2_1/c$ (#14)	
Unit cell dimensions	a = 8.1391(8) Å	α = 90°.
	b = 26.986(3) Å	β = 114.683(2)°.
	c = 7.5735(7) Å	γ = 90°.
Volume	1511.4(3) $Å^3$	
Z	4	
Density (calculated)	1.482 Mg/m^3	
Absorption coefficient	2.731 mm^{-1}	
F(000)	696	
Crystal size	0.50 x 0.40 x 0.30 mm^3	
Theta range for data collection	2.75 to 27.00°.	
Index ranges	–10<=h<=10, –34<=k<=34, –9<=l<=9	
Reflections collected	14017	
Independent reflections	3306 [R(int) = 0.0269]	
Completeness to theta = 27.00°	99.9 %	
Absorption correction	Semi–empirical from equivalents	
Max. and min. transmission	0.4946 and 0.3733	
Refinement method	Full–matrix least–squares on F^2	

Data / restraints / parameters	3306 / 0 / 256
Goodness–of–fit on F^2	1.045
Final R indices [I>2sigma(I)]	R1 = 0.0244, wR2 = 0.0593
R indices (all data)	R1 = 0.0290, wR2 = 0.0614
Largest diff. peak and hole	0.439 and –0.223 e.Å^{-3}

Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters (Å^{2}x 10^3) for **191a**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Atom	x	y	z	U(eq)
Br	2705(1)	632(1)	3773(1)	17(1)
C(1)	8535(3)	5129(1)	6566(3)	23(1)
N(1)	7223(2)	4723(1)	5798(2)	17(1)
C(2)	6827(2)	4395(1)	6879(3)	16(1)
C(3)	7643(3)	4375(1)	9022(3)	23(1)
N(2)	5558(2)	4092(1)	5645(2)	14(1)
C(4)	5181(2)	4230(1)	3760(3)	17(1)
C(5)	6215(2)	4624(1)	3856(3)	19(1)
C(6)	4701(2)	3676(1)	6149(3)	16(1)
C(7)	5785(2)	3208(1)	6432(2)	14(1)
O(1)	7248(2)	3176(1)	6418(2)	22(1)
O(2)	4841(2)	2830(1)	6675(2)	19(1)
C(8)	5533(2)	2333(1)	6684(3)	19(1)
C(9)	3952(3)	2006(1)	5598(3)	20(1)
O(3)	2887(2)	1963(1)	6680(2)	20(1)
C(10)	1096(2)	1806(1)	5486(3)	20(1)
C(11)	2(3)	1814(1)	6663(3)	20(1)
O(4)	561(2)	1425(1)	8038(2)	22(1)
C(12)	–364(3)	1444(1)	9272(4)	32(1)

213m

Crystal data and structure refinement for **213m**.

Identification code	**213m**	
Empirical formula	$C_{15}\ H_{18.64}\ N_2\ O_{4.82}\ Br$	
Molecular formula	$[C_{15}\ H_{17}\ N_2\ O_4]^+[Br]^-$ x 0.82 ($H_2\ O$)	
Formula weight	386.73	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P1 (#1)	
Unit cell dimensions	a = 8.9583(10) Å	α = 76.132(2)°.
	b = 9.7659(11) Å	β = 71.333(2)°.
	c = 11.1941(12) Å	γ = 63.809(2)°.
Volume	826.95(16) $Å^3$	
Z	2	
Density (calculated)	1.553 Mg/m^3	
Absorption coefficient	2.512 mm^{-1}	
F(000)	395	
Crystal size	0.60 x 0.50 x 0.10 mm^3	
Theta range for data collection	1.93 to 28.30°.	
Index ranges	–11<=h<=11, –12<=k<=13, –14<=l<=14	
Reflections collected	16930	
Independent reflections	8130 [R(int) = 0.0223]	
Completeness to theta = 28.30°	99.7 %	
Absorption correction	Semi–empirical from equivalents	
Max. and min. transmission	0.7873 and 0.4272	
Refinement method	Full–matrix least–squares on F^2	

Data / restraints / parameters	8130 / 7 / 432 [a)]
Goodness–of–fit on F^2	1.038
Final R indices [I>2sigma(I)]	R1 = 0.0394, wR2 = 0.0956
R indices (all data)	R1 = 0.0421, wR2 = 0.0972
Absolute structure parameter	0.010(6)
Largest diff. peak and hole	1.430 and –0.835 e.Å^{-3}

[a)] The O–H bond lengths were restrained to be 0.84 Å DFIX.

Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters (Å^{2}x 10^3) for **213m**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Atom	x	y	z	U(eq)
C(1)	5458(4)	9054(4)	4686(3)	24(1)
N(1)	3854(3)	9022(3)	5563(2)	16(1)
C(2)	3165(4)	9541(4)	6692(3)	18(1)
N(2)	1703(3)	9339(3)	7205(2)	16(1)
C(3)	2814(4)	8454(4)	5347(3)	23(1)
C(4)	1470(4)	8646(4)	6379(3)	20(1)
C(5)	574(4)	9757(3)	8443(3)	18(1)
C(6)	904(4)	8349(3)	9424(3)	16(1)
O(1)	1817(3)	7073(3)	9183(2)	21(1)
O(2)	–7(3)	8777(2)	10571(2)	19(1)
C(7)	294(4)	7569(3)	11604(3)	20(1)
C(8)	314(4)	8208(4)	12702(3)	23(1)
O(3)	1317(4)	7520(3)	13348(3)	35(1)
O(4)	–941(3)	9588(3)	12876(2)	24(1)
C(9)	–1038(5)	10281(4)	13927(3)	30(1)
C(10)	–1062(4)	6902(3)	12007(3)	18(1)
C(11)	–2632(4)	7700(4)	11699(3)	20(1)
C(12)	–3858(5)	7060(4)	12134(3)	26(1)

C(13)	–3507(6)	5657(5)	12874(3)	33(1)
C(14)	–1954(6)	4862(4)	13172(4)	35(1)
C(15)	–703(5)	5469(4)	12728(3)	29(1)
C(16)	–4984(6)	4861(5)	10173(4)	29(1)
N(3)	–3178(3)	4142(3)	10225(2)	20(1)
C(17)	–2082(4)	4820(3)	9784(3)	20(1)
N(4)	–601(3)	3845(3)	10053(2)	19(1)
C(18)	–2370(4)	2688(4)	10796(3)	22(1)
C(19)	–758(4)	2507(3)	10694(3)	23(1)
C(20)	960(4)	4122(4)	9683(3)	23(1)
C(21)	2180(4)	3323(3)	8532(3)	17(1)
O(5)	1986(3)	2471(3)	8047(2)	21(1)
O(6)	3528(3)	3713(3)	8147(2)	20(1)
C(22)	4748(4)	3084(3)	7007(3)	17(1)
C(23)	3825(4)	3744(3)	5938(3)	16(1)
O(7)	2618(3)	4932(3)	5905(2)	24(1)
O(8)	4594(3)	2809(3)	5028(2)	24(1)
C(24)	3762(5)	3281(5)	3980(3)	33(1)
C(25)	6204(4)	3584(3)	6738(3)	17(1)
C(26)	5878(4)	5085(4)	6842(3)	21(1)
C(27)	7226(5)	5525(4)	6594(3)	26(1)
C(28)	8908(5)	4483(4)	6223(4)	29(1)
C(29)	9233(4)	2984(4)	6100(4)	28(1)
C(30)	7885(4)	2527(4)	6369(3)	22(1)
Br(1)	7108(1)	8734(1)	7862(1)	24(1)
Br(2)	2904(1)	1278(1)	2123(1)	41(1)
O(9)	3373(4)	9050(4)	–4(3)	37(1)
O(10) [a)]	6069(6)	1288(5)	9722(4)	31(1)

[a)] s.o.f. = 0.637(9) (s.o.f.: site occupation factor)

213n

Crystal data and structure refinement for **213n**.

Identification code	**213n**	
Empirical formula	$C_{15}\ H_{18.68}\ N_2\ O_{4.84}\ Br$	
Molecular formula	$[C_{15}\ H_{17}\ N_2\ O_4]^+[Br]^-$ x 0.84 ($H_2\ O$)	
Formula weight	386.73	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P1 (#1)	
Unit cell dimensions	a = 8.9698(4) Å	α = 76.203(1)°.
	b = 9.7824(5) Å	β = 71.446(1)°.
	c = 11.1834(5) Å	γ = 63.689(1)°.
Volume	828.42(7) $Å^3$	
Z	2	
Density (calculated)	1.550 Mg/m^3	
Absorption coefficient	2.507 mm^{-1}	
F(000)	395	
Crystal size	0.70 x 0.50 x 0.40 mm^3	
Theta range for data collection	1.93 to 31.65°.	
Index ranges	–12<=h<=13, –14<=k<=13, –16<=l<=16	
Reflections collected	19676	
Independent reflections	10094 [R(int) = 0.0143]	
Completeness to theta = 30.00°	99.8 %	
Absorption correction	Semi–empirical from equivalents	
Max. and min. transmission	0.4337 and 0.2612	
Refinement method	Full–matrix least–squares on F^2	

Data / restraints / parameters	10094 / 7 / 432 [a)]
Goodness–of–fit on F^2	1.062
Final R indices [I>2sigma(I)]	R1 = 0.0358, wR2 = 0.0884
R indices (all data)	R1 = 0.0384, wR2 = 0.0897
Absolute structure parameter	0.002(4)
Largest diff. peak and hole	1.829 and –1.250 e.Å^{-3}

[a)] The O–H bond lengths were restrained to be 0.84 Å DFIX.

Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters (Å^{2}x 10^3) for **213n**. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Atom	x	y	z	U(eq)
C(1)	4549(3)	933(3)	5305(2)	22(1)
N(1)	6154(2)	967(2)	4431(2)	15(1)
C(2)	6836(3)	455(2)	3297(2)	14(1)
N(2)	8305(2)	654(2)	2791(2)	15(1)
C(3)	7196(3)	1530(3)	4654(2)	20(1)
C(4)	8536(3)	1346(3)	3619(2)	19(1)
C(5)	9428(3)	239(2)	1549(2)	15(1)
C(6)	9098(3)	1640(2)	579(2)	14(1)
O(1)	8193(2)	2922(2)	813(2)	19(1)
O(2)	10010(2)	1212(2)	–580(2)	17(1)
C(7)	9698(3)	2430(2)	–1611(2)	16(1)
C(8)	9689(3)	1769(3)	–2708(2)	19(1)
O(3)	8671(3)	2461(2)	–3349(2)	31(1)
O(4)	10958(2)	393(2)	–2885(2)	21(1)
C(9)	11056(4)	–295(3)	–3937(2)	26(1)
C(10)	11046(3)	3093(2)	–2008(2)	16(1)
C(11)	12623(3)	2300(3)	–1716(2)	18(1)
C(12)	13842(3)	2937(3)	–2147(2)	23(1)

C(13)	13481(4)	4353(3)	–2878(2)	29(1)
C(14)	11917(4)	5145(3)	–3165(3)	31(1)
C(15)	10677(4)	4529(3)	–2729(2)	25(1)
C(16)	14979(4)	5154(4)	–174(3)	27(1)
N(3)	13184(3)	5857(2)	–235(2)	18(1)
C(17)	12091(3)	5177(3)	208(2)	18(1)
N(4)	10609(2)	6143(2)	–60(2)	17(1)
C(18)	12362(3)	7311(3)	–802(2)	20(1)
C(19)	10747(3)	7491(3)	–698(2)	21(1)
C(20)	9049(3)	5864(3)	314(2)	21(1)
C(21)	7830(3)	6670(2)	1459(2)	16(1)
O(5)	8023(2)	7527(2)	1946(2)	20(1)
O(6)	6489(2)	6276(2)	1846(2)	18(1)
C(22)	5271(3)	6902(2)	2989(2)	14(1)
C(23)	6195(3)	6242(3)	4058(2)	15(1)
O(7)	7421(2)	5051(2)	4081(2)	22(1)
O(8)	5427(2)	7173(2)	4969(2)	21(1)
C(24)	6241(4)	6699(4)	6022(2)	27(1)
C(25)	3820(3)	6403(2)	3256(2)	14(1)
C(26)	4151(3)	4902(3)	3151(2)	19(1)
C(27)	2797(3)	4462(3)	3393(2)	23(1)
C(28)	1118(3)	5502(3)	3760(3)	26(1)
C(29)	795(3)	6997(3)	3879(3)	26(1)
C(30)	2135(3)	7459(3)	3616(2)	18(1)
Br(1)	2886(1)	1261(1)	2141(1)	22(1)
Br(2)	7103(1)	8737(1)	7875(1)	38(1)
O(9)	6609(3)	972(3)	10006(2)	33(1)
O(10) [a)]	3947(4)	8705(3)	267(3)	30(1)

[a)] s.o.f. = 0.682(7) (s.o.f.: **s**ite **o**ccupation **f**actor)