Phosphonium Ion Based Salen Derivatives for Use in Catalysis

By
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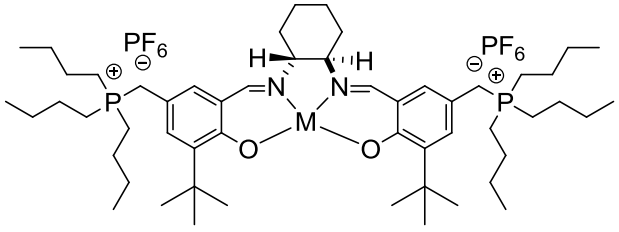
Abstract

Schiff base ligands and their respective complexes are well established for use in asymmetric catalysis. With difficulty of separation of the catalyst from reaction mixtures being one of the more salient drawbacks to these systems, much recent work has been directed towards developing methods that allow easy recovery and reuse of the catalyst. The incorporation of phosphonium ionic cores into asymmetric salen ligands to generate a Task Specific Ionic Liquid (TSIL) could promote entrainment of the catalyst in an ionic liquid (IL). With the catalyst firmly immobilized in the ionic liquid layer, this forms a recyclable system whereby the desired product can be extracted, leaving the catalyst behind in the IL for reuse. The ligand, 5,5'-(1E,1'E)-(1R,2R)-(cyclohexane-1,2-diylbis(azan-1-yl-1-ylidene))bis(methan-1-yl-1-ylidene)bis(3-tert-butyl-4-hydroxy-5,1-phenylene)bis(methylene)bis(tributylphosphonium)hexafluorophosphate, as well its respective copper (II) and manganese (III) complexes were successfully synthesized and characterized.

Aziridination reactions were catalysed by the copper complex with a phosphonium ion tagged ligand, in both 1-butyl-3-methylimidazolium hexafluorophosphate, [bmim][PF_6], and 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide, [bmim][$N(Tf)_2$] ionic liquids. The catalyst was recycled several times in both ILs without appreciable loss in product yield over successive runs. Recycling of the manganese complex in the epoxidation of styrene was performed in both [bmim][PF_6] and [bmim][$N(Tf)_2$], with moderate to full conversion of substrate into product being observed for successive runs in each ionic liquid.



M = Cu(II), Mn(III)

April 25th, 2014

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"Success is the ability to go from one failure to another with no loss of enthusiasm" –
Winston Churchill

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Abbreviations

$[bmim]^+$	1-butyl-3-methylimidazolium
CEAR	Center for Environmental Analysis and Remediation
$CDCl_3$	deuterated chloroform
cP	centipoise
DCM	dichloromethane
EA	elemental analysis
ee	enantiomeric excess
$[emim^+]$	1-ethyl-3-methylimidazolium
EPA	Enviromental Protection Agency
ESI-MS	electrospray ionization mass spectrometry
HKR	Hydrolytic Kinetic Resolution
HRMS-ESI	high resolution mass spectrometry
ILs	ionic liquids
IR	infrared
m.p	melting point
m-CPBA	meta-chloroperoxybenzoic acid
$[MeIm]^+$	1,3-dimethylimidazolium
NaOCl	sodium hypochlorite
NMR	nuclear magnetic resonance
NMR^3	Nuclear Magnetic Resonance Research Resource
$[NTf_2]^-$	bis(trifluoromethanesulfonimide)
$[PF_6]^-$	hexafluorophosphate
PhI=NTs	*N*-tosyliminophenyliodinane
PTC	phase transfer catalyst
RT	room temperature
RTIL	room temperature ionic liquid
salen	N,N'-bis(salicylidine)ethylenediamine
TBAI	tetrabutylammonium iodide
TMS	tetramethylsilane
TSILs	task specific ionic liquids
VOCs	volatile organic compounds

1.0 Introduction

1.1 Green Chemistry

With concern over environmental impact experiencing a surge in the last two decades, many areas of scientific research and industry have begun to pursue less harmful processes. In particular, the increasing need for more sustainable technologies has directed attention towards the use of atom efficient catalytic methodologies in the synthesis of fine chemicals and pharmaceuticals.[1] This push towards a safer means of practicing science, underlines the principles that govern what is referred to as 'green chemistry'. Although still in its infancy, having only been introduced in 1990, green chemistry is supported by numerous initiatives such as the US Environmental Protection Agency (EPA)[2] which aims to ensure that green chemistry continues to receive adequate attention and financial support. Although it is widely acknowledged that there exists the need for more environmentally viable processes in chemical industry, much work remains if we are to truly exercise green chemistry on a large scale. When probing what is necessary for sustainable technology to flourish, green chemistry expert Dr. Roger Sheldon suggests that we must move away from explaining process efficiency solely in terms of chemical yield, and move to one that assigns economic value to the reduction of waste at the source and facilitates the avoidance of using hazardous substances.[1]

Used to gauge how 'green' a process is, the E-factor was introduced as a means to measure the potential environmental acceptability of a given chemical process in terms of the waste generated relative to useful products. The E-factor, which is simply the mass ratio of waste to desired product, reveals just how wasteful various segments of chemical industry are upon comparing their E-factor values[2] (Table 1).

Table 1. E-factor values of selected industrial segments.[2]

	Tonnage	E = kg waste/kg product
Bulk Chemicals	10^4-10^6	<1-5
Fine Chemicals	10^2-10^4	5 - 50
Pharmaceutical	10-10^3	25 -> 100

As is evident, waste production is much more significant for pharmaceuticals than it is for fine and bulk chemical processes, a result that stems from the use of multi-step syntheses and stoichiometric reagents.[2] In particular, the fine chemical and pharmaceutical processes often feature outdated stoichiometric technologies that produce large amounts of inorganic waste. Accounting for a significant amount of waste in organic synthesis, these salts are often un-desirable products in numerous stoichiometric reactions in industry such as reductions with metals, sulfonations, nitrations, halogenations and Friedel-Crafts acylations.[1] To combat this problem, it has been suggested that cleaner catalytic methods will reduce the high level of waste that accompanies the use of stoichiometric inorganic reagents.[1,3,5]

With pollution prevention becoming more of a pressing matter, scientists are increasingly exploiting more of their synthetic tools to promote safer processes.[1] To provide a framework for scientists when designing new materials, products, and processes, the twelve principles of green chemistry were introduced as a way of directing our methodology in the greenest manner possible. In brief, these principles aim to promote the reduction or elimination of hazardous substances in the design, manufacturing and application of chemical products.[3] Although it may not be possible to exercise all of the principles simultaneously, even incremental changes can have profound effects on pollution prevention. As such, all aspects of a synthesis should be considered when attempting to design greener processes.[3]

When considering the largest contributors to global waste, it will be found that solvent usage accounts for an incredible amount. This is in large part attributed to the inclusion of solvents in nearly all manufacturing and processing industries, where nearly 15 billion kilograms of organic and halogenated solvents are produced worldwide each year.[4] The most concerning issue with such high solvent usage stems from the fact that removal of residual solvent from products is typically achieved by evaporation or distillation as many solvents are highly volatile. This inevitably leads to atmospheric pollution on a large scale. As such, the need to limit solvent usage is currently one of the more pressing matters in green chemistry.[5] However, because volatile organic compounds (VOCs) are so firmly entrenched in the field of chemistry, owing to their desirable properties and applicability in such a wide scope of reactions, prompting the reduction of solvent usage is no easy task.

Fortunately, significant strides over the last few decades have been made in green chemistry and the use of alternative solvents is being increasingly considered. Examples of these less conventional solvent alternatives include; supercritical water, fluorous phases, supercritical carbon dioxide, and ionic liquids.[4,6] These alternatives have shown promise for aiding in the reduction, recovery, and re-usage of solvents and are being increasingly investigated. Ionic liquids in particular have received a considerable amount of attention as a viable alternative solvent due in large part to their greener properties and wider scope of applicability in comparison to VOCs.

1.2 Ionic Liquids

Ionic liquids (ILs) represent a class of compounds that have received significant recognition in the field of green chemistry as alternative solvents, owing to their unique and desirable properties. These ideal characteristics include negligible vapour pressure, thermal stability and the ability to solvate a wide variety of compounds. Considerable progress has been made in the application of room temperature ionic liquids (RTILs) in catalytic processes as they have the potential to serve as 'greener' reaction media.

Ionic liquids are typically defined as salts that exist in the liquid state below 100°C. Their relatively low melting points have been attributed to the presence of unsymmetrical alkyl groups on the cation[7]; however the melting point of ILs have been shown to be influenced by the nature of the anion as well.[8] A variety of names have been used over the years to describe ionic liquids, which include room-temperature molten salt, liquid organic salts, low melting molten salts, and molten salts.[1] As ILs are often liquid at low temperatures and exhibit comparatively low viscosities, they are often distinguished from the classical definition of molten salts, which refers to a high-melting, highly viscous medium.[7]

These versatile salts are typically comprised of a bulky organic cation, accompanied by an inorganic, frequently halogenated anion. With there being a significant number of suitable cations and anions known, the potential number of ILs is immense. Despite the vast potential for variability in ILs, the cations most often featured are; tetraalkylammonium, tetraalkylphosphonium and 1,3-dialkylimidazolium ions, while typical anions include; halides, hexafluoridophosphate, bis(trifluoromethanesulfonimide), and tetrafluoridoborate (Figure 1).

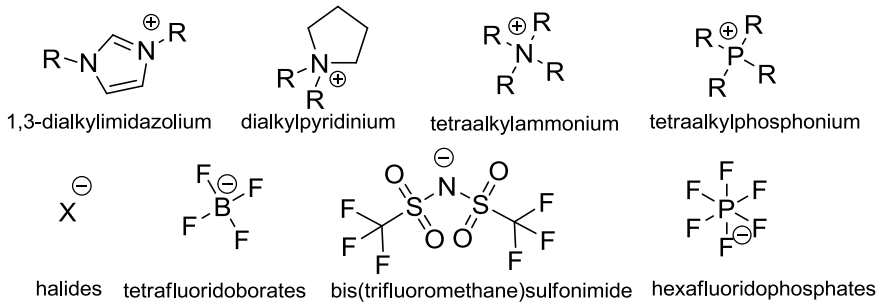


Figure 1. Typical cations and anions featured in ionic liquids.

1.2.1 History of Ionic Liquids

Despite only recently seeing increased exposure in scientific literature, ILs are certainly not a new class of compounds, with examples of these liquid salts dating back centuries.[9] The first reporting of a substance possessing characteristics that define an ionic liquid came in the mid-19th century when a red oily material was the observed product of a Friedel-Crafts reaction. This oily substance was identified much later as a salt upon use of nuclear magnetic resonance (NMR) spectroscopy.[9]

Chloroaluminate based ionic liquids were first observed in 1951 where they saw inclusion in various electrochemical applications.[10] Being the first ionic liquids to show potential for industrial application, these compounds helped solidify the use of the term 'ionic liquids' when describing these low-melting salts.[9] Advancements in chloroaluminate based systems came in the late 1970s when Osteryoung *et al.* succeeded in developing room-temperate liquid choloroaluminate melts.[10] Although these compounds primarily found use in electrochemical applications, the discovery of 1-ethyl-3-methylimidazolium ([emim$^+$]) chloride based chloroaluminate ionic liquids (Figure 2) in 1982 drastically increased interest in this area prompting the investigation of these compounds in other applications such as solvent usage.[11]

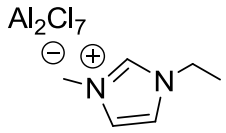


Figure 2. An example of the room-temperature chloroaluminate salts synthesized by Wilkes *et al.*[11]

The first instances of ionic liquids being used as a reaction solvent for homogenous catalysis were described separately by Wilkes *et al.* and Chauvin *et al.* in 1990.[12,13] Wilkes' group studied ethylene polymerization catalyzed by a Ziegler-Natta catalyst in weakly acidic chloroaluminate ionic liquids.[12] As for Chauvin *et al.*, they investigated the dimerization of propene upon dissolving nickel catalysts in weakly acidic chloroaluminate melts.[13] Despite chloroaluminate systems finding use in several electrochemical studies such as the ones mentioned previously, their sensitivity to water and air prevented their introduction into other applications.[11]

Water stable ionic liquids such as 1-butyl-3-methylimidazolium hexafluoridophosphoric acid ([bmim][PF_6]) emerged in 1990 where enhanced stability against hydrolysis compared with chloroaluminate ionic liquids was reported by Wilkes and Zaworotko.[14] These systems were found to have higher tolerance for functional groups, opening up a much broader range of applications for ILs, particularly for transition metal catalysis. Building on initial discoveries, much work has since been carried out in order to gain a deeper appreciation for the physical and chemical properties of ionic liquids.

1.2.2 Properties of Ionic Liquids

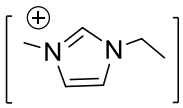
Contrary to traditional solvents, ILs exhibit negligible volatility which gives allows for their use as recyclable solvents, an aspect that has made use of these compounds a popular area of chemical research. Although exploiting the non-volatility of ILs is often the focus, they also

possess numerous other desirable characteristics that include; thermal stability, biodegradability, and the ability to solvate a wide variety of compounds. With their broad liquidus range, combined with their high degree of solvability, ionic liquids are suitable for a wide range of reactions, a distinction which separates them from traditional solvents.[9]

The melting points of ionic liquids are found to be much lower in comparison to metal salts. For example, sodium chloride melts at 803°C, whereas 1-butyl-3-methylimidazolium chloride, [bmim][Cl], melts at a much lower 65°C.[9] To rationalize this, Seddon *et al.* proposed that their low melting points can be attributed to low symmetry, weak intermolecular interactions, and efficient charge distribution in the cation.[15] This explanation is supported by comparison of the melting points of the 1,3-dimethylimidazolium based cation ($[Me_2im]^+$) and its substituted derivatives; as introduction of a butyl group at the 1-position reduces the melting point by 60°C.[9] Altering the length of these alkyl chains has been shown to have significant affects on the hydrophobicity of ILs and highlights the ability to tune specific properties of these compounds.

The nature of the anion has been shown to affect the melting point of ionic liquids. Several theories have been evoked to explain the inverse relationship between anion size and IL melting point such as reduction of Coulombic attraction contributions, increased covalency of ions, as well as hydrogen bonding effects between cation and anion.[9] A survey of the melting points for various $[emim^+]X^-$ based ionic liquids show just how marked an effect substitution of anion can have (Table 2).[16]

Table 2. Anion effects on the melting point of [emim$^+$] based ionic liquids.[16]

Cation	Anion	m.p (°C)
	Cl^-	87
	NO_3^-	55
	$AlCl_4^-$	7
	BF_4^-	6
	$CF_3SO_3^-$	-9

1.2.3 Synthesis of Ionic Liquids

Ionic liquid synthesis can generally be split into two parts: formation of the desired cation, followed by anion exchange to introduce the desired anion. In many instances the cation of choice is commercially available as the halide salt, thus needing only anion exchange to complete the synthesis.[9] Conversely, there are some cases where anion exchange is not necessary, such as the formation of ethylammonium nitrate.[9] Generation of the cation is often carried out by either protonation with a free acid, or by quaternization of a phosphine or amine, typically with a haloalkane.[16] Due to less harsh reaction conditions being required, along with the accessibility of a variety of inexpensive haloalkanes, the latter method is preferred and is applicable to a wider scope of ionic liquids.[9]

Once the desired cation is formed, the synthesis of the IL can be completed with exchange of the anion (in cases where this is required). For water-immiscible ionic liquids, the preparation is more straightforward in comparison to hydrophilic analogues.[9] For these systems, an aqueous solution of a halide salt of the selected cation is prepared followed by anion exchange

with the acid of the desired anion. Alternatives to the free acid approach do exist however, such as the metathesis of a halide salt with metal or ammonium salts (Figure 3).[16] Ensuring that the formed IL is free of undesirable cations or anions is crucial for anion exchanges in ionic liquids. This is clearly a less laborious task for water-immiscible ionic liquids as repeated water washings is often sufficient to ensure the IL is uncontaminated by residual ions.

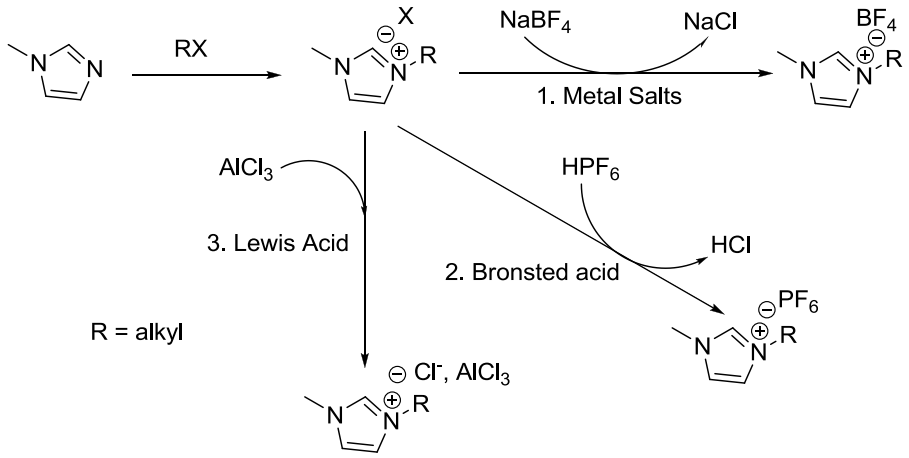


Figure 3. Common synthetic route for ionic liquids.[16]

As for the preparation of water-miscible ionic liquids, more demanding procedures are required to obtain pure products free of halide contaminants. As in the preparation of water-immiscible ILs, water soluble ILs can be prepared through anion exchange in an aqueous solution with either a free acid, ammonium, or an alkali metal salt. For this approach, it is critical to ensure that the desired ionic liquid be free of contamination from unwanted halide containing by-products. Welton *et al.* developed an alternative approach while preparing [bmim][BF_4], where the product into dichloromethane (DCM) followed by rigorous washing of the organic phase.[17] Once the washings are pH neutral and there is no evidence of halide ions being present, the DCM layer is removed and further purified using activated charcoal. The metathesis is completed by filtering the liquid through a short neutral alumina column followed by removal of

solvent and drying *in vacuo*. Although reduced yields can be expected for this method, it allows the formation of pure ILs, thus making this a viable method in most applications.[9]

1.2.4 Task Specific Ionic Liquids

How one tailors the synthesis of their ILs is not limited to only varying the cation and anion. It is possible also to functionalize these compounds, and this modification allows for their use in a variety of pre-determined applications. The functional groups of ILs can be manipulated in such a way as to perform specific functions, giving rise to what is known as Task Specific Ionic Liquids (TSILs). Through logical design of the ionic liquid, they can be utilized in a wide scope of applications which include; catalysis, lubricants, catalyst anchoring, electrochemistry, and metal ion separation.[9] This concept is well illustrated in the work of Harjani *et al.*, where metal ion remediation was demonstrated using a novel family of TSIL salts with aminodiacetic acid functionality, for the removal of copper from aqueous solution (Figure 4). [18] In this work, control of the hydrophobicity and solubility of the metal complexes was essential to their success, and it was achieved by altering the length of the alkyl chains introduced into the TSIL.

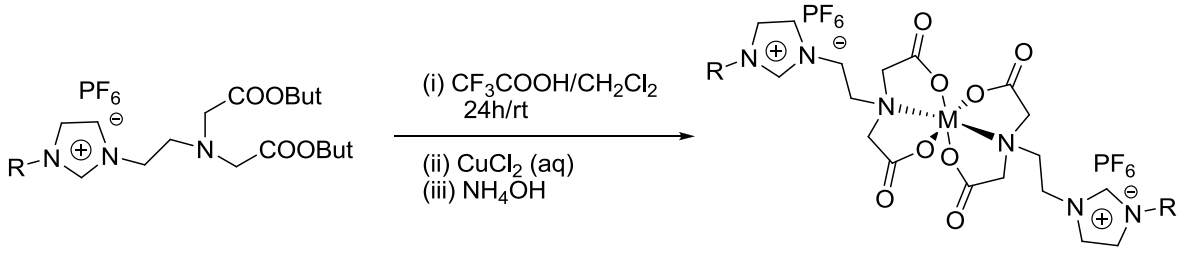


Figure 4. An aminodiacetic acid TSIL used by Harjani *et al.* for metal ion remediation.[18]

Bates *et al.* demonstrated the ability to perform CO_2 capture with task specific ionic liquids where they used an imidazolium based ionic liquid with the cation being covalently tethered to a primary amine.[19] They were able to show that this novel salt readily and reversibly

sequesters CO_2 and recycled the IL up to five times with no appreciable loss in efficiency. Although the relatively high viscosity of the IL used in their work (Figure 5) limits its potential use in large-scale application, they anticipate that they will be able to design a variant with improved physical and chemical properties.

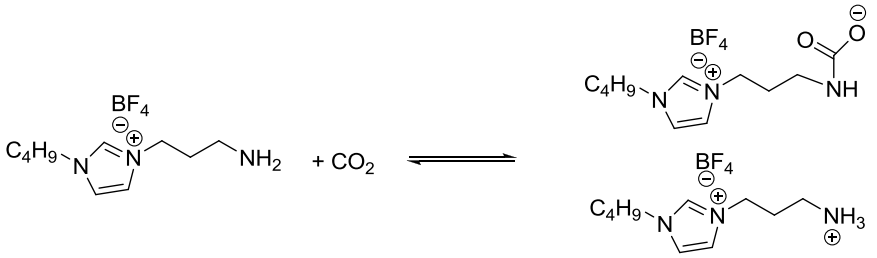


Figure 5. Proposed reaction scheme by Bates *et al.* between a TSIL and CO_2.[19]

It is clear that with the introduction of task specific ionic liquids, the scope of applications that ILs can partake in is immense. The incorporation of ionic liquid moieties into functionalized molecules allows a greater range of utility compared to traditional solvents. Although only a few examples have been presented, many cases exist citing the use of a TSIL in a host of applications. As such, the scope of applications for ionic liquids is increasingly expanding.

1.3.0 Organic Reactions in Ionic Liquids

1.3.1 Diels-Alder Reactions

Given the versatility of ionic liquids as solvents, it can be imagined that they can play host to a variety of chemical reactions. Indeed, many organic and organometallic reactions performed in ionic liquids have been reported, with the authors often citing enhanced reactivity in ionic liquds in comparison to traditional solvents. Diels-Alder reactions, one of the most

useful carbon-carbon bond forming reactions in organic synthesis, has recently been shown to benefit from being performed in an IL.[20,21]

The first Diels-Alder reaction performed in an ionic liquid was reported by Jaëger *et al.* where they studied the reaction of cyclopentadiene with methyl acrylate in $[EtNH_3]NO_3$.[20] It was found that rate and stereoselectivity enhancements were achieved relative to those obtained in conventional organic solvents.[20] Welton's group recently studied the same reaction, where they investigated the effect of solvent by using a wide range of ionic liquids such as $[bmim][PF_6]$ (Figure 6).[21] They reported substantial increases in *endo*-selectivity and rate enhancements in comparison to non-polar solvents. They concluded that ionic liquids with the strongest hydrogen-bond donor cation coupled with the weakest hydrogen-bond accepting anion allowed for greatest selectivity.

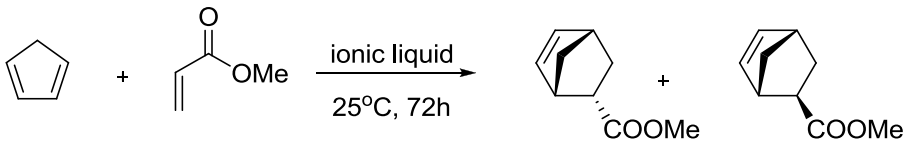


Figure 6. Diels-Alder reaction between cyclopentadiene and methyl acrylate performed in an ionic liquid, as reported by Welton *et al.*[21]

1.3.2 Suzuki Cross Coupling Reactions

Another important carbon-carbon bond forming method such as the Suzuki cross-coupling reaction have been investigated in an ionic liquid as well. The Suzuki coupling reaction is well known as a versatile method for the generation of new C-C bonds, in particular for the synthesis for biaryls. Despite their success, conventional Suzuki reactions suffer from several

drawbacks such as separation of catalyst from products, catalyst decomposition, and poor reagent solubility.[22]

Aiming to mitigate these problems, Matthews *et al.* investigated the Suzuki reaction in an ionic liquid.[23] By using ILs, they found that several of the problems associated with Suzuki coupling could immediately be addressed. Owing to their high polarity, ionic liquids are able to solvate a wide variety of organic and inorganic compounds. With ionic liquids being resistant to thermal decomposition over a broad temperature range, Matthews and co-workers found that great rate enhancement could be observed in comparison to general conditions employed, by conducting reactions at 110°C.

For example, the coupling of 4-bromotoluene with phenylboronic acid catalyzed by a triphenylphosphine Pd(0) complex was carried out in the ionic liquid [bmim][BF_4], affording the coupled biphenyl in 93% yield in 10 minutes. This is a marked improvement on traditional ethereal based Suzuki couplings, where the same reaction was found to afford 88% yield after 6 hours. Finally, with typical extracting solvents such as ether being immiscible with common ionic liquids, isolation of coupled products free of catalyst contamination can be achieved.

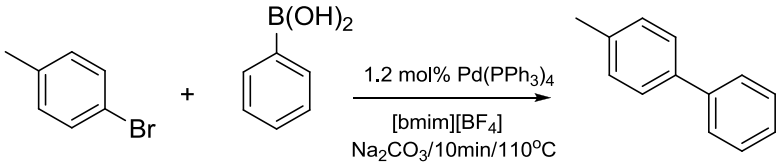


Figure 7. An ionic liquid mediated Suzuki cross-coupling reported by Matthews *et al.* between an aryl halide and phenylboronic acid.[23]

1.3.3 Wittig Reactions

The Wittig reaction represents one of the most popular methods in organic synthesis for forming C=C bonds. Although the Wittig reaction is a powerful method for stereoselective olefin synthesis, the separation of alkene from the phosphine oxide by-product still remains a significant drawback.[24] Classically, the Ph_3PO by-product has been removed by crystallization or by chromatography. Recently the use of ionic liquids has been found to facilitate easier removal of the unwanted phosphine oxide[24]; the reaction of various aromatic and aliphatic aldehydes with phosphorus ylides using [bmim][BF_4] as the solvent, gave both high yields (90%) and selectivity (96/4 for E/Z). Through careful choice of extracting solvents, both the product and phosphine oxide by-product could be isolated separately allowing facile re-use of the ionic liquid for subsequent reactions.

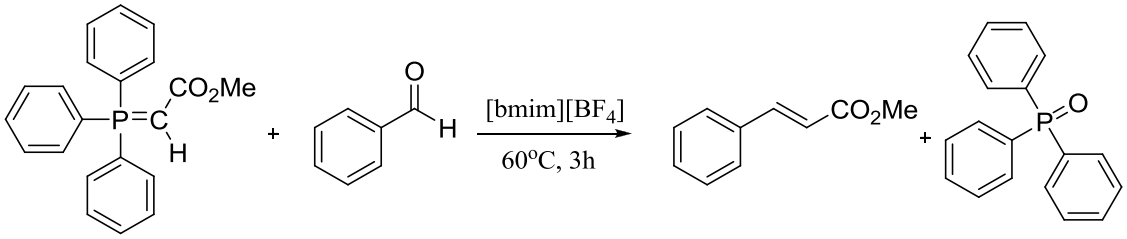


Figure 8. Wittig reaction performed in an ionic liquid, reported by Le Boulaire *et al.*[24]

1.4.0 Salen Ligands

Schiff bases represent an attractive class of compounds receiving considerable attention over the years owing to their ability to chelate a variety of transition metals. Salen ligands (N,N'-bis(salicylidine)ethylenediamine), are a subset of Schiff bases that are prepared via condensation of two equivalents of a salicylaldehyde derivative and one equivalent of a diamine. The most facile amine used in preparation of salen ligands is ethylenediamine. Through introduction of a

chiral backbone onto the ligand such as *trans*-1,2-diaminocyclohexane, the possibility arises to perform asymmetric catalysis.

Though they are a relatively new class of compounds, salen ligands and their corresponding complexes are well established in the field of asymmetric catalysis owing to their success in stereoselective reactions and relatively inexpensive syntheses.[25] This is in large part due to the work of Jacobsen *et al.*, who through logical structure design, synthesized the now famous Jacobsen's ligand, which is renowned for its performance in asymmetric epoxidations of un-functionalized olefins (Figure 9). Metal complexes of Jacobsen's ligand have since been successfully applied to a broad range of important asymmetric reactions.[26,27]

While designing his ligand, Jacobsen investigated a host of variations, including ligands derived from chiral 1,2-, 1,3-, and 1,4-diamines, chiral tertiary 1,2-diamines and hydroxyacetophenones. After exploring an exhaustive list of ligand designs, it was found that the ligand featuring a diaminocyclohexane backbone containing bulky alkyl substituents at the 3,3'- and 5,5'- positions possessed the optimal balance between high selectivity for a broad range of substrates as well as accessibility from inexpensive raw materials.[28]

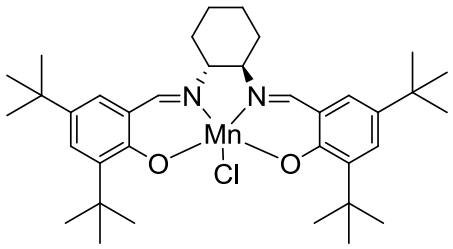


Figure 9. Structure of Jacobsen's Catalyst.

Based on the success of Jacobsen's model, many groups began to tailor the design of their own ligands around the principals that make Jacobsen's catalyst so efficient. Originally

designed for use in epoxidations of un-functionalized olfeins, the success of Jacobsen's catalyst led to its modification and investigation in a variety of other asymmetrically catalyzed reactions, such as epoxide ring opening, cyclopropanations, aziridinations, and selective hydrogenations.[30]

1.4.1 Epoxidations Catalyzed by Salen-Metal Complexes

Owing to their relatively simple and inexpensive syntheses, salen ligands and their corresponding complexes have been modified for inclusion in a variety of catalytic processes. One of the earliest examples of these compounds being used in catalysis came in 1990 when Jacobsen *et al.* reported the enantioselective epoxidation of unfunctionalized olefins.[29] More than two decades removed from this initial report, the optimized conditions established for salen based epoxidations have proven to exhibit superior utility and practicality in comparison to variations studied (Figure 10).[29,30]

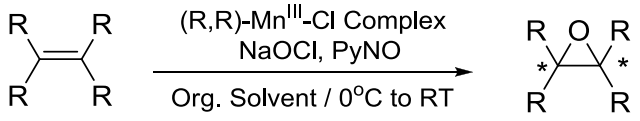


Figure 10. Optimized conditions for asymmetric epoxidations.[29]

The catalyst used in these systems (Figure 9), is a salen-manganese(III) complex bearing stereogenic carbon atoms at C1' and C2' positions of the backbone.[30] Although the C3 and C3' substituents are achiral, their presence has been found to be essential for achieving high enantioselectivity. The profound effects the C3 and C3' substituents have on catalytic efficiency was rationalized by Jacobsen *et al.* by suggesting that bulky groups at these positions direct the approaching substrate towards the chiral backbone allowing for efficient translation of stereochemical information.[29]

Epoxidation reactions catalyzed by salen-manganese(III) complexes are typically carried out using a catalytic amount of the Mn^{III}-Cl complex (1-10%) along with 1-2 equivalents of a terminal oxidant. These reactions are often performed at room temperature in traditional solvents such as acetonitrile and dichloromethane. It is worth noting that although these reactions are very capable of proceeding to completion at room temperature in relatively short reaction times, lowering the temperature from zero to -20°C has shown in some cases to promote higher enantioselectivity.[31] Typical terminal oxygen sources used are iodosobenzene and sodium hypochlorite, whereas less frequently used sources include hydrogen peroxide, peroxy acids, and molecular oxygen.

The mechanism for these oxygen transfer reactions consists of a two step catalytic cycle. In the first step, a salen-Mn^{V} oxo complex is formed, followed by delivery of the activated oxygen to the olefinic double bond (Figure 11).[30]

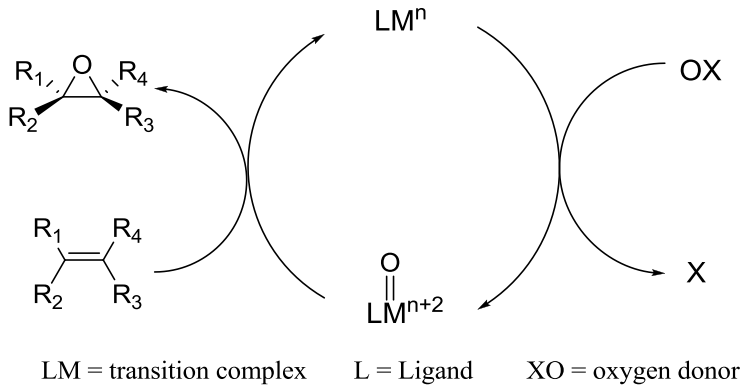


Figure 11.Proposed mechanism for transition metal-catalyzed epoxidations.[30]

Although the first step in the catalytic cycle is widely accepted, the manner in which the oxygen is delivered to the olefin in the second step is not mutually agreed upon.[35] Transfer of the oxygen atom from the oxo-metal species to the olefin has been suggested to proceed *via* several

intermediates that include a concerted transition state, carbon radical, carbocation or a π-radical cation.[32,33] As the stereochemistry is tied to the first transition state for oxygen delivery to the olefin, knowledge of this step proves invaluable in optimizing reaction conditions to obtain highest enantioselectivity.[30] With the structural requirements needed to obtain the high enantioselectivity having since been optimized for Jacobsen's like catalysts, the exact mechanism of the oxygen delivery step is one of the more investigated aspects of these systems.

1.5.0 Epoxides

1.5.1 Properties of Epoxides

An epoxide is a three-membered, oxygen containing heterocycle, also known as a cyclic ether. The simplest epoxide, oxirane, consists of an oxygen and two carbon atoms. Three-membered heterocyclic rings are synthetically useful in the sense that they offer a unique combination of reactivity, synthetic flexibility, and atom economy.[34] Although epoxides are typically not the end product in any synthetic sequence, their balance between stability and reactivity make them highly versatile as synthetic intermediates. The strain of these compounds rings explain their high reactivity and they can readily be attacked by nucleophiles under mild conditions, resulting in ring opening of the epoxides to afford a variety of functionalized compounds. One of the major reasons epoxides are viewed as such attractive synthetic intermediates stems from the possibility to introduce two adjacent stereogenic centers, as such epoxides have seen extensive use in asymmetric ring-opening reactions.[35-37]

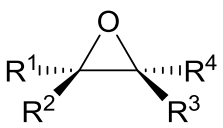


Figure 12. General structure of an epoxide.

1.5.1 Synthesis of Epoxides

The synthesis of epoxides can be subdivided into three general categories: metal catalyzed, non-metal catalyzed, and biological. The most widely used non-metal catalyzed method for synthesizing epoxides is the reaction of an alkene with an organic peroxy acid.[38] One of the most useful peroxy acid reagents to carry out the epoxidation of olefins is meta-chloroperoxybenzoic acid (*m*-CPBA). The reaction is thought to proceed *via* a single-step "butterfly" mechanism that involves nucleophilic attack of the alkene π-electrons onto the peracid.[39] This results in the *syn* addition of the oxygen to the alkene, with the formation of an epoxide and a carboxylic acid.

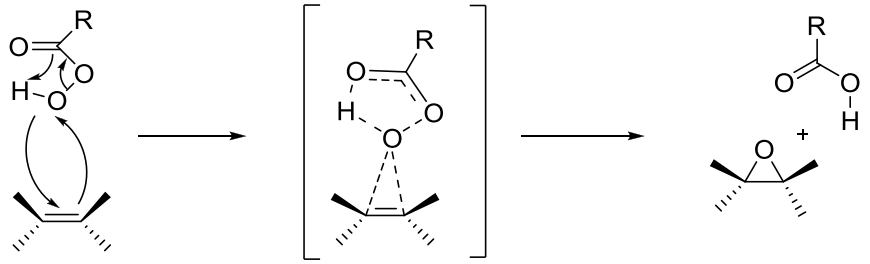


Figure 13. Concerted mechanism for olefin peroxidation.[38]

Metal mediated systems for epoxidation reactions were introduced in 1965 by Indictor *et al.*, who used metal acetylacetonate complexes to activate *t*-butyl hydroperoxide (TBHP).[40] The alkene is thought to coordinate to an empty coordination site on the metal, positioning it for attack on the electrophilic peroxide. Through investigation with several metal sources, they determined that metals of high oxidation states were best equipped to catalyze epoxidation reactions.

An important methodology for catalyzing enantioselective epoxidations came in 1980 when Katsuki and Sharpless described an efficient system for the asymmetric epoxidation of

allylic alcohols.[41] This method involves a combination of a titanium (IV) alkoxide, a chiral tartarate ester, and an alkyl hydroperoxide. The Sharpless-Katsuki method quickly became one of the cornerstones of asymmetric synthesis as this catalytic system is able to epoxidize a wide range of allylic alcohols in good yields and enantiomeric excesses exceeding 90%. An important feature of this catalytic process is the requirement for substrates to possess allylic alcohol functionality. This requirement stems from the fact that the allylic alcohol coordinates to the metal during catalytic epoxidations. The allylic alcohol moiety then activates the oxidant and controls the delivery of oxygen to the substrate, preferentially to one of the two enantiotopic faces of the alkene.[42]

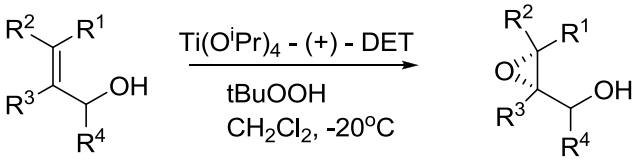


Figure 14. Reaction scheme for the Sharpless epoxidation.[41]

Despite the Sharpless epoxidation representing an important advancement in the field of asymmetric catalysis, the requirement of allylic alcohol functionality on the substrate limits its use in many applications. This prompted the investigation into development of a more tolerable catalytic system and in 1990 Jacobsen and Katsuki independently reported the synthesis of salen manganese(III) complexes capable of achieving superior enantioselectivity in comparison to previously used models.[30]

In contrast to the Sharpless epoxidation, in which the substrate pre-coordinates with the catalyst, the Jacobsen-Katsuki epoxidation achieves high chiral induction *via* non-bonding interactions.[29] The challenge of controlling the olefin approach to the oxidant guided Jacobsen when designing his ligand and found that *t*-butyl substituents at the 3,3' and 5,5' positions had

sufficient bulk necessary to guide the incoming towards the metal center, which is in close proximity of the stereogenic carbons of the catalyst. This results in excellent stereochemical communication between the olefin and catalyst allowing for enantiomerically enriched products.[43]

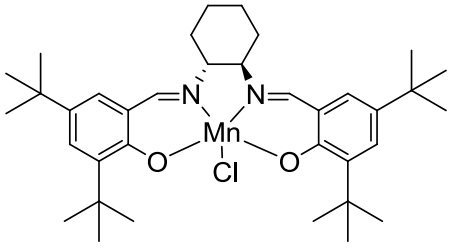


Figure 15. Structure of Jacobsen's catalyst.

1.5.2 Utility of Epoxides

Due to the ring strain accompanying epoxides, they represent one of the most versatile organic subunits in organic synthesis and can be viewed as acceptor (a2) synthons. Not surprisingly, many methods for opening epoxide rings are known, and are dominated by nucleophilic substitution reactions (Figure 16).[39]

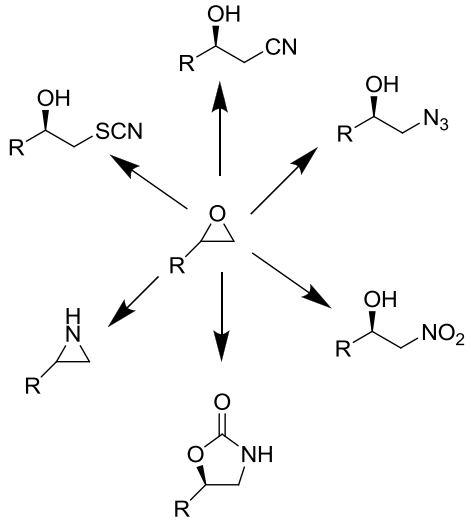


Figure 16. Examples of nucleophilic reactions of epoxides.[39]

Epoxide ring opening *via* acid catalysis is one common method, whereby the acid assists epoxide ring opening by providing a better leaving group (an alcohol) at the carbon atom undergoing nucleophilic attack.[40] In acid-catalyzed ring openings of an asymmetric epoxide, the nucleophile attacks primarily at the most substituted carbon atom. Though this may seem counterintuitive given steric considerations, the protonated epoxide intermediate resembles a 3^o carbocation, leaving a greater positive charge on the susceptible carbon atom.[40] Epoxides can be ring opened in base catalyzed reactions as well, provided the attacking nucleophile is a strong base such as an alkoxide or hydroxide ion. In basic ring opening reactions, the nucleophile attacks from the less substituted side.

Following the discovery of salen manganese (III) complexes as enantioselective catalysts for the epoxidation of un-functionalized olefins, curiosity arose as to whether similar complexes could perform asymmetric ring-openings of epoxides.[44] To test this, Jacobsen *et al.* investigated a series of metal complexes for the ring opening of cyclohexene oxide by trimethylsilylazide ($TMSN_3$). After screening several metal complexes it was found that a chromium (III) based complex was the most effective catalyst with regard to both reactivity and enantioselectivity. It was found that remarkable selectivity could be obtained in the kinetic resolution of terminal epoxides using the (salen)-CrN_3/$TMSN_3$ system (Figure 17).

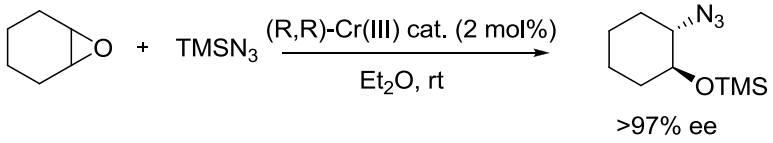


Figure 17. Enantioselective epoxide ring opening catalyzed by a salen-Cr(III) complex.[44]

Epoxides have also been investigated in hydrolytic kinetic resolution (HKR) reactions mediated by salen complexes, where chiral nonracemic epoxides could be obtained from their

racemates.[45] Jacobsen *et al.* were able to resolve racemic epichlorohydrin in the presence of a cobalt catalyst, and a slight excess of water under solvent-free conditions (Figure 18).[45]

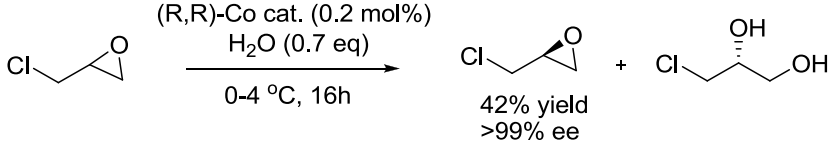


Figure 18. Hydrolytic kinetic resolution of epichlorohydrin catalyzed by a salen catalyst.[45]

1.6 Previous Group Work

The use of a TSIL for selected applications has been an ongoing project in the Singer group for several years. TSILs suitable for catalysis have been prepared by incorporating IL moieties into a variety of common ligands used to chelate transition metals. Imidazolium based moieties for example have been added to salen ligands in the preparation of both copper (II) and manganese (III) chloride complexes (Figure 19) for selected catalysis by Naik *et al.*[46] The manganese (III) chloride complex (10 mol%) was used to catalyze the epoxidation of selected olefins using iodosobenzene as the oxidant. The reactions were performed in [bmim][PF_6] and for some instances, such as in the epoxidation of styrene, quantitative yield could be obtained.

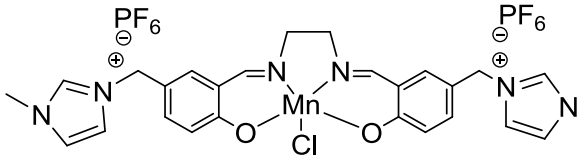


Figure 19. Previously synthesized imidazolium tagged salen complex for use in catalysis.[46]

Durand synthesized an analogous methylimidazolium tagged ligand but incorporated a 1,2-diaminocyclohexane backbone into the ligand rather than ethylenediamine to allow for its

potential use in asymmetric catalysis (Figure 20).[48] This version of the catalyst also featured *tert*-butyl groups at the 3,3' positions, which has been shown to allow for enhanced stereoselectivity.[43] The saldach ligand designed by Durand was complexed to copper (II) and its catalytic activity was tested in aziridination reactions. It was found that moderate yields of aziridine proudct could be obtained in acetonitrile (56%), however only low yields were found for reactions conducted in an ionic liquid (19%).

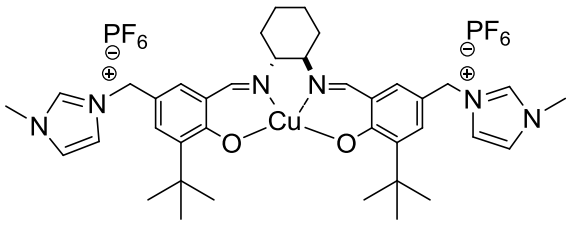


Figure 20. Previously synthesized imidazolium copper (II) saldach complex.[47]

The most recent study featured the synthesis of an asymmetric saldach ligand with tri-*n*-butylphosphonium moieties in the 5,5' positions of the salicylaldehyde derivative.[48] The anticipation was that the steric bulk accompanying the corresponding phosphonium complex, would allow for better stereoselectivity in comparison to its imidazolium analogue. The resulting copper (II) complex (Figure 21) was used to catalyze the aziridination of styrene using a 10 mol% of catalyst, and it was found that higher yields could be obtained in acetonitrile (88%) than for the imidazolium containing ligand. Despite good yields being obtained in conventional solvents, no efficient protocol was established for conducting reactions in an ionic liquid

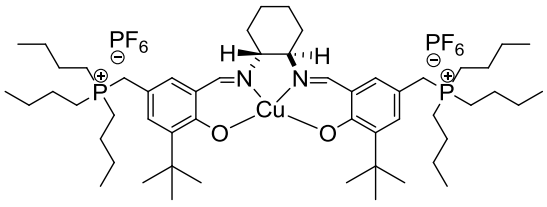


Figure 21. Previously synthesized phosphonium copper (II) saldach complex.[47]

1.7 Objective

With the focus of work done in Singer group to promote and practice the principles of green chemistry, tailoring the design of a salen-type catalyst to be compatible in an ionic liquid would help achieve this task. The ionic character of the designed catalysts, **5** and **6**, will ideally make them highly soluble in the chosen IL solvents, allowing for facile isolation of products and ultimately the recycling of the catalyst. The overall goal of this project is to synthesize an asymmetric phosphonium ion based saldach ligand, **4b**, and complex it to both copper and manganese. The resulting copper (II), and manganese (III) complexes, **5** and **6** respectively (Figure 22), will have their catalytic activity in an ionic liquid medium tested in aziridination and epoxidation reactions.

Another aim of this work is to achieve enhanced catalytic activity. It is anticipated that the incorporation of tributylphosphonium moieties onto the salen ligand will afford products in high enantiomeric excesses as a result of its steric bulk. The Cu (II) complex will be used to catalyze the aziridination of styrene and the Mn (III) complexes will be used to catalyze the epoxidation of styrene with the goal of developing a recyclable system in an ionic liquid for both systems. Once optimal conditions are established for the ideal reactant stoichiometry, the stereoselectivity of all synthesized products will be evaluated by means of chiral LC analysis.

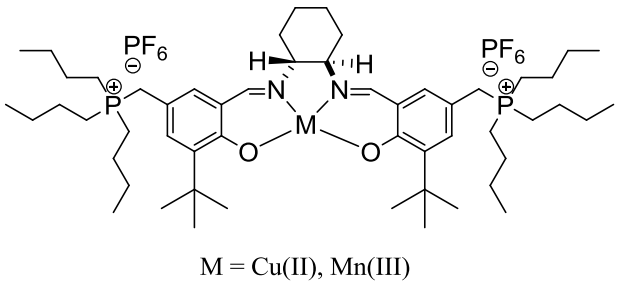


Figure 22. Targeted IL-salen Cu(II) and Mn(III) catalysts, **5** and **6**.

2.0 Results and Discussion

2.1 Synthesis of the Saldach Copper (II) and Manganese (III) Complexes

The five step synthesis of the saldach-IL ligand, **4**, and copper complex, **5a**,**5b**, was carried out in accordance with the procedure described by Prudhoe,[48] with any modifications made to the procedure being noted in the following discussion. The racemic and asymmetric manganese IL-saldach complexes, **6a,6b**, were prepared according to the literature procedure of Tan *et al.*[49]

The synthesis began with the readily available starting material, 3-*tert*-butyl-2-hydroxybenzaldehyde, which was chloromethylated to afford 3-*tert*-butyl-5-chloromethyl-2-hydroxybenzaldehyde, **1.** Compound **1** was then used to alkylate tri-*n*-butylphosphine to yield 3-*tert*-butyl-5-formyl-4-hydroxybenzyl)phosphonium chloride, **2.** The crude chloride salt was then metathesized to afford the hexafluoridophoshate salt, **3**. The PF_6 salt, **3,** then underwent a condensation reaction with racemic and enantiopure *trans*-1,2-diaminocyclohexane to afford racemic and asymmetric 5,5'-cyclohexane-1,2-diylbis(azan-1-yl-1-ylidene)bis(methan-1-yl-1-ylidene)bis(3-tert-butyl-4-hydroxy-5,1-phenylene)bis(methylene)bis(tributylphosphonium), saldach phosphonium ligand, **4a** and **4b**, respectively (Figure 23). The racemic and asymmetric copper (II) complexes, **5a,b,** were prepared by refluxing the ligand, **4a,4b,** with copper (II) acetate monohydrate in methanol. Similarly, the racemic and asymmetric manganese (III) complexes, **6a, 6b,** were prepared by refluxing the ligand, **4a,4b**, with manganese acetate tetrahydrate in ethanol.

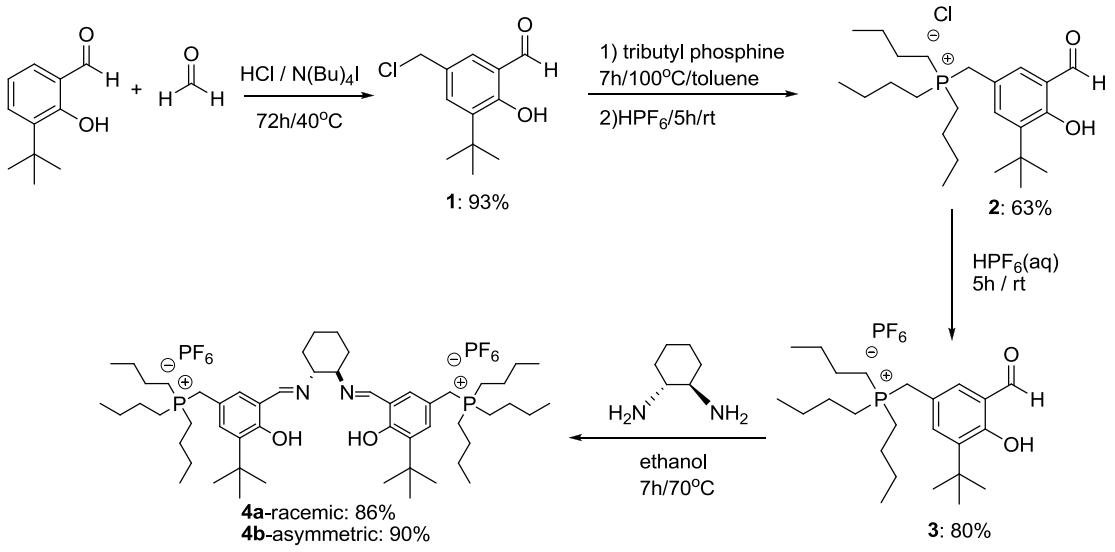


Figure 23. Reaction scheme for the formation of the racemic and asymmetric IL saldach ligand, **4a,4b**.

The syntheses of **5** and **6** begun with the chloromethylation of 3-*tert*-butyl-2-hydroxybenzaldehyde. The procedure of Durand[48] was followed for this step, which is a modification of the original procedure proposed by Canali *et al.*,[50] with an iodide based phase-transfer catalyst being used instead of the bromide version. The chloromethylation was carried out by reaction of the salicylaldehyde derivative with paraformaldehyde in concentrated HCl for 72 hours at 40°C. This reaction took place in the presence of tetrabutylammonium iodide, which acts as a phase-transfer catalyst (PTC) in the reaction. A phase-transfer catalyst serves to enhance the rate of reaction by facilitating the migration of one reactant into a phase it would not normally be soluble in.[51] In this particular reaction, the PTC assists the transfer of the organic substrate 3-*tert*-butyl-2-hydroxybenzaldehyde into the aqueous phase.

This modified procedure resulted in the separation of a dark red oil from the reaction mixture. To isolate the product, the aqueous layer was extracted with portions of diethyl ether

resulting in an ethereal solution that was dark red in color. Durand[47] had previously determined that this color stemmed from the presence of molecular iodine, and was able to remove the residual iodine by washing the organic layer with portions of sodium bisulfite. Washing with sodium bisulfate is known to remove iodine by converting it to iodide, which is colorless and soluble in water. This procedure was followed and immediately resulted in a pale yellow ether solution. Removal of the solvent afforded the pure product 3-*tert*-Butyl-5-chloromethyl-2-hydroxybenzaldehyde, **1**, as a yellow solid in 93% yield, and was characterized by both ^{1}H and ^{13}C NMR spectroscopy.

The mechanism for the chloromethylation of 3-*tert*-butyl-2-hydroxybenzaldehyde, **1**, is thought to proceed in two steps, beginning with an electrophilic aromatic substitution, followed by an S_N1 type reaction (Figure 24).[52] The acidic reaction medium serves two purposes for this reaction, the first being protonation of the paraformaldehyde to generate the electrophile. It also protonates the hydroxymethyl portion of the salicylaldehyde derivative in the second step of the mechanism, making it an ideal leaving group. In the first step, the π electrons of the salicylaldehyde derivative attack the electrophilic carbon, temporarily eliminating aromaticity. Removal of a hydrogen by a water molecule re-establishes aromaticitiy, which ends the electrophilic aromatic substitution portion of the mechanism.[52] The protonated hydroxymethyl group is then lost, resulting in a benzylic carbocation, which is attacked by available chloride ions to generate the final product.

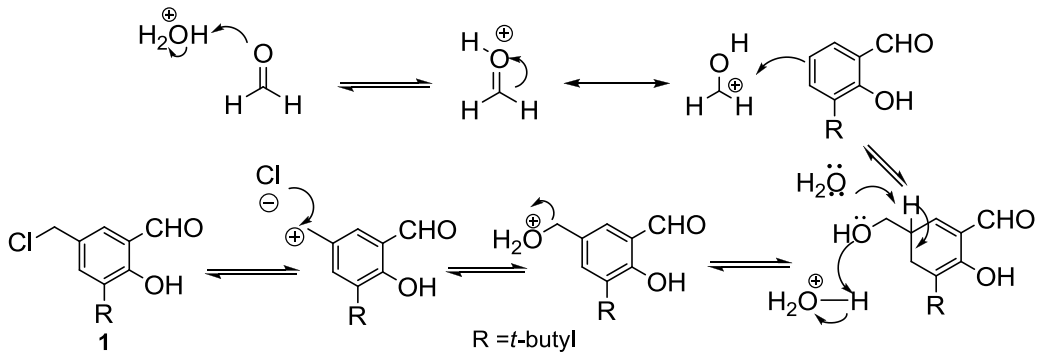


Figure 24. Mechanism for the chloromethylation of 3-*tert*-butyl-2-hydroxybenzaldehyde, **1**.[52]

The chloromethylated product, **1**, is then used in the quaternization reaction with tri-*n*-butylphosphine to afford tributyl(3-*tert*-butyl-5-formyl-4-hydroxybenzyl)phosphonium chloride, **2**. Due to its sensitivity to moisture in the air, tri-*n*-butylphosphine was transferred to a round bottom flask in an inert atmosphere glove box where it was dissolved in dry toluene. The phosphine solution was then added dropwise *via* syringe to a round bottom flask containing a toluene solution of the chloride compound **1**, which was under inert N_2 atmosphere using Schlenk techniques. The reaction mixture was left to reflux for seven hours before removal of the solvent afforded the crude chloride salt, **2.** Owing to its hygroscopic nature, the chloride salt was difficult to purify. Previous work done by Prudhoe[48] aiming to improve the overall yield of this reaction, revealed that by directly performing anion exchange on the crude product with aqueous hexafluoridophosphoric acid (HPF_6), a higher yield of the PF_6 salt, **3**, could be obtained. This procedure was followed and the crude chloride salt underwent metathesis to the hexafluoridophosphate salt without further purification to afford **3,** in 80% yield.

The alkylation of tri-*n*-butylphosphine to produce the chloride salt, **2,** likely proceeds in an S_N2 fashion, with the Lewis basic lone pair of electrons on the phosphorous attacking the reactive benzyllic carbon of compound **1** (Figure 25). The chloromethylated salicylaldehyde derivative acts as an electrophile in this reaction, with the methylene carbon bearing a partial

positive charge, which arises from being adjacent to a more electronegative chlorine atom. The resulting positive charge from the formed quaternary phosphonium salt is balanced by the displaced chloride ion.

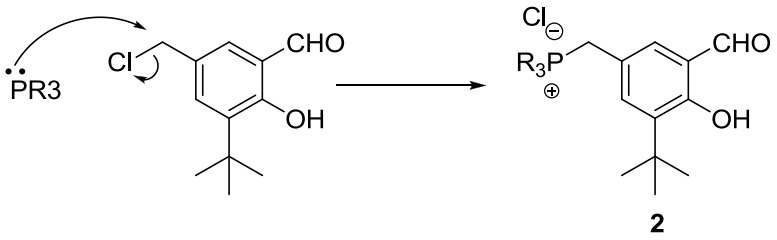


Figure 25. Mechanism for the alkylation of tri-*n*-butylphosphine to yield compound **2.**

The metathesis of the crude chloride salt, **2**, is carried out in water at room temperature. The hygroscopic chloride salt, **2**, is first dissolved in water before the addition of 65% w/w hexafluoridophosphoric acid. It was found that slow dropwise addition of the acid is required to prevent the PF_6 salt, **3**, from precipitating too rapidly from the solution, which could potentially entrap halide impurities.

Previous description of this reaction by Prudhoe[48] cited difficulties with the isolation and purification of the hexaflouridophosphate salt, referencing the formation of a sticky green and white clumpy solid. However, it was found that by shortening the reaction time from 24 hours to five hours, no clumping occurred and a pure white solid could be isolated. The isolated white solid was confirmed to be the desired product, (3-tert-butyl-5-formyl-4-hydroxybenzyl)phosphonium hexaflurophosphate, **3**, by ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy. The phosphorous NMR spectrum of **3** displays two signals, the first being a singlet at 31.5 ppm, which corresponds to the phosphorous cation. A septet is observed at -144 ppm, which arises from the ^{1}J coupling of the phosphorous to the fluorine atom on the PF_6 anion. A crystal structure of **3** was obtained by Prudhoe (Figure 26),[48] which indicates successful alkylation of tri-*n*-

butylphosphonium. The crystal structure also confirms the presence of the hexafluoridophosphate anion that balances the positive charge on the phosphorous atom.

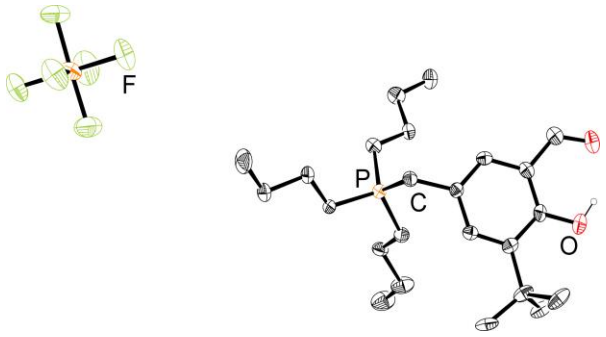


Figure 26. X-ray crystal structure obtained by Prudhoe[48] of compound **2**.

Water represents an ideal solvent choice for the metathesis reaction owing to the hydrophobic nature of hexafluoridophosphate based ionic liquids. As the chloride salt, **2**, readily dissolves in an aqueous medium; the hydrophobic product, **3**, can easily be isolated by filtration as it immediately precipitates. With the product, **3**, being insoluble in water, the reaction is driven forward due to the effects of Le Chatelier's principle, with equilibrium being shifted towards product formation as product is removed from solution.

Once compound **3** was successfully synthesized and characterized, reaction with 1,2-diaminocyclohexane was conducted to generate the ligand, **4a,4b**. (R,*R*)-1,2-diaminocyclohexane was chosen as the diamine source instead of a simple reagent such as ethylenediamine, to prepare an asymmetric ligand. To prepare both the racemic and asymmetric ligand, an ethanol solution of the diamine reagent was added to an ethanol solution of **3**, which resulted in the immediate formation of a yellow solution. In the preparation of the racemic ligand, **4a**, racemic-*trans*-1,2-diaminocyclohexane was used, and enantiomerically pure R,R-*trans*-1,2-diaminocyclohexane was used to form the chiral ligand, **4b**. The resulting mixture was

left to reflux for seven hours and upon cooling to room temperature, a light yellow solution containing precipitate was observed. This is in contrast to what was observed by Prudhoe[49], as the racemic ligand, **4a**, was not found to precipitate, and column chromatography was required to purify the compound. This was later attributed to the use of impure diamine reagent, and subsequent reactions carried out with pure diamine source consistently resulted in precipitation of the product. The reaction mixture was placed in the freezer overnight to further promote precipitation, and the product was filtered and washed with cold ethanol to afford a light yellow solid. As most salen ligands are a bright yellow solid, the light yellow color of the obtained product was concerning at first; however dissolution in chloroform affords a bright yellow solution, which when evaporated leaves a bright yellow solid. The resulting product was identified by ESI MS, ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy to be saldach phosphonium ligand, **4**. The method of vapour diffusion was employed by using chloroform and diethyl ether in attempt to obtain a crystal structure of the ligand; however no X-ray quality crystals were obtained. The ^{31}P NMR spectrum displayed similar peaks at 31.6 and -144 ppm to those found for **3**, indicating the phosphonium moiety of the ligand is intact. No peaks were observed in the ^{1}H NMR spectrum that would suggest the presence of free diamine contamination. The imine bond formed is indicated by the disappearance of the aldehyde signal in the ^{1}H NMR spectrum at 9.90 ppm, along with the appearance of a new peak at 8.34 ppm.

Noted prior, the formation of the ligand is an example of a condensation reaction. This type of reaction refers to the coming together of two reactants to from a larger compound, while also eliminating a smaller molecule, typically water. For this condensation reaction, the two molecules coming together are the ligand precursor **2,** and 1,2-diaminocyclohexane, with the smaller molecule lost being water.[53] With condensation reactions, the rate of reaction can be

affected by the initial presence of water. This is tied to the fact that since water is a product of this reaction, its presence would inhibit the forward reaction. To avoid this problem, absolute ethanol was used to minimize the amount of water initially present in the reaction.

The synthesis of the copper (II) complex, **4a,4b**, from the ligand was performed in accordance with the procedure of Prudhoe (Figure 27)[48]. A methanol solution of copper (II) acetate was added dropwise to a methanol solution of the ligand **4a** or **4b**, which resulted in the immediate formation of a dark purple solution. The mixture was left to reflux for six hours and upon cooling to room temperature, a purple precipitate was observed. The reaction mixture was left in the freezer overnight to further promote precipitation of the product from solution. The product was isolated *via* filtration to afford a dark purple powder which was washed with cold methanol. High yields were obtained for both versions of the complex, generating a 90% and 93% yield for the racemic and asymmetric complexes, respectively. The prepared complexes were characterized by HRMS-ESI to confirm their identity, with a molecular ion peak appearing at 462.7939 m/z.

The original synthesis of the manganese (III) complex, **6**, from the ligand was based upon previous work by Naik *et al.*, in which the ligand precursor **3** is reacted with both the diamine and desired metal salt, resulting in the *in* situ formation of the ligand followed by complexation.[46] However, as the corresponding manganese (III) complex is paramagnetic, its purity cannot be measured by simple NMR methods. Therefore for this work, it was desirable to isolate and characterize the ligand first before subjecting it to complexation. Once the ligand, **4a,4b**, was characterized, it was used to prepare the manganese (III) complex by reaction with manganese acetate tetrahydrate and lithium chloride, following the procedure of Tan *et al.*[49] This was carried out by introducing an ethanol solution of manganese (II) acetate tetrahydrate

dropwise to an ethanol solution of **4a** or **4b.** This resulted in the immediate formation of a dark brown solution, which was left to reflux for five hours. Once the resulting mixture had cooled to room temperature, an ethanol solution of lithium chloride was added. The solution was left to stir at room temperature for several hours before air was bubbled into the reaction mixture for fifteen minutes to oxidize the manganese (II) metal to manganese (III). The chloride ions present in solution could then ideally coordinate to the metal center, generating the manganese (III) complex, **6a,6b**. The reaction mixture was left in the freezer overnight to further promote precipitation of the product from solution. The product was isolated *via* filtration to afford a dark brown powder which was washed with water affording a moderate 66% and 70% yield for the racemic and asymmetric complexes, respectively. The synthesized complexes were characterized by IR, ESI-MS and HRMS-ESI to confirm its identity, with a molecular ion peak in the HRMS-ESI appearing at 476.2803 m/z. Elemental analysis was performed in order to confirm the identity of the product. The results for hydrogen and nitrogen were in close agreement with the calculated values (both within 0.10% of expected value). The analysis for carbon however was off by 1.2% therefore further purification steps are required to obtain percentages that better resemble the calculated values.

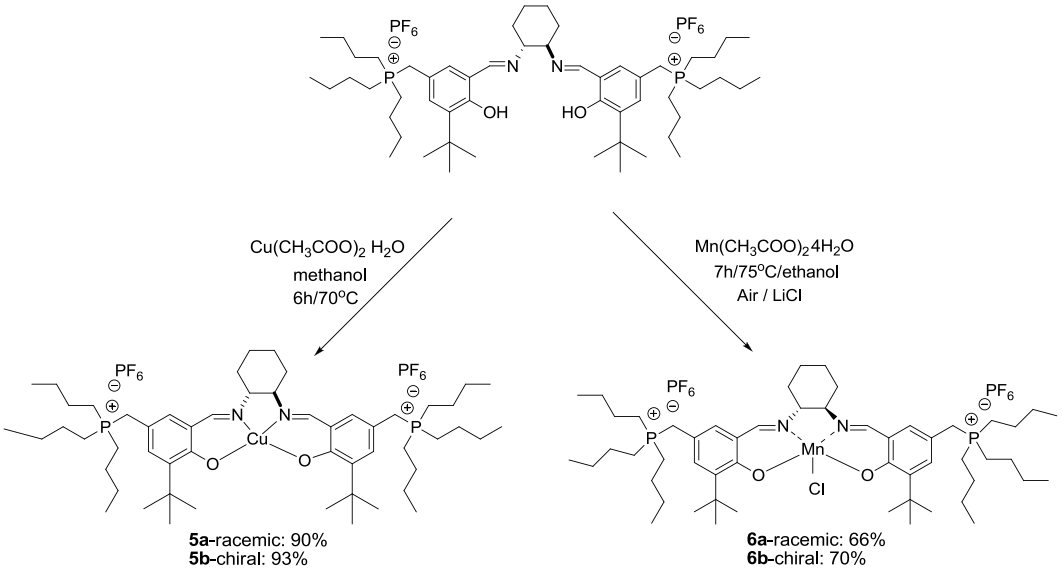


Figure 27. The reaction scheme for the synthesis of phosphonium saldach copper (II), **5**, and manganese (III), **6**, complexes.

X-ray quality crystals of the chiral manganese (III) complex were obtained by preparing a saturated ethanol solution of **6b**, which was used to make a series of two-fold dilutions. Of the eight solutions prepared, one trial produced tiny crystals suitable for X-ray diffraction. The X-ray crystal structure of **6b**-$(EtOH)_2$ was obtained (Figure 28).

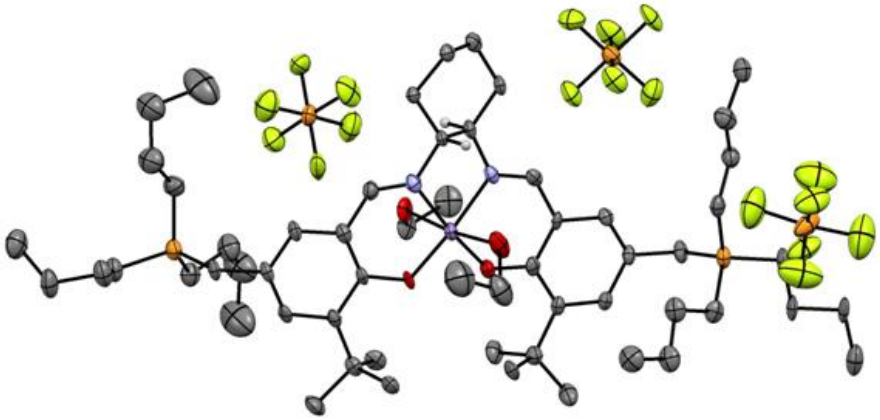


Figure 28. X-ray structure of the IL-saldach-manganese complex **6b**-$(EtOH)_2$.

The X-ray structure obtained for compound **6b** did not match the expected structure of the complex (Figure 22). The expected compound is a square pyramidal manganese (III) salen complex with an axial chloride ligand coordinated to the metal. In the X-ray crystal structure, a solvate was obtained with two ethanol molecules coordinated to the metal centre, making it an octahedral manganese (III) cation with a third PF_6 anion present to balance the charge on the metal. Although the crystal structure does not match the expected structure, **6b,** it was originally thought that the major species existing in solution was in fact a Mn(III)-Cl complex. This is borne from the fact that obtained characterization data, (ESI-MS, HR ESI-MS), correlate well with the values that would be expected for a Mn^{III}-Cl complex. However, as the ESI-MS spectrum does not display a characteristic m+2 isotope peak that would be expected for a compound containing a chlorine atom, it cannot be unequivocally stated that the Mn(III) chloride complex was ever successfully synthesized.

Work by Butler *et al.* investigating salen Mn(III) chloride solvate crystal structures reported the weakening of the Mn-Cl bond in donor solvents, which allows the chloride ion to dissociate from the metal resulting in a $Mn(salen)^+$ species.[54] In this instance, it is thought that the $Mn(salen)^+$ complex could scavenge a PF_6 anion from un-reacted ligand to generate the structure seen in the X-ray structure. However, as there is no chloride m+2 isotope peak present in the ESI-MS spectrum this conclusion cannot be made and a more thorough investigation into this structure is required.

2.2 Catalytic Reactions in an Ionic Liquid

Once compounds **5a,5b**, and **6a,6b**, were successfully synthesized and characterized, their catalytic ability in aziridination and epoxidation reactions was investigated. Interest in these

systems is based on many examples of catalytically active salen metal complexes having been reported in literature.[30,46,55]

2.2.1 Aziridinations

Prudhoe was the first to investigate the catalytic ability of the copper complexes **5a,5b**, where the aziridination of styrene was performed using *n*-tosyliminophenyliodinane (PhI=NTs), as the nitrene source.[48] The inexpensive substrate styrene was chosen as the olefin as it is a common model compound for testing the catalytic activity of salen complexes. Initial reactions were conducted in acetonitrile, which is well established as a conventional solvent for salen-Cu complex mediated aziridinations. The catalyst, **5a,5b**, was used with a loading of 10 mol % based on the limiting reagent. Previous work by Durand[47] found that for aziridinations catalyzed by IL-salen-Cu complexes (Figure 20), a five-fold excess of styrene relative to PhI=NTs generated the highest yield. Under these optimized reaction conditions, Prudhoe was able to obtain yields of 84% and 88% of the 2-phenyl-1-tosylaziridine product catalyzed by copper compounds **5a,5b,** respectively. Although high yields were obtained for reactions carried out in CH_3CN, no efficient protocol was developed for catalyzing aziridinations in an ionic liquid.

Building on work by Durand[47] and Prudhoe[48], this study was directed towards developing an effective method for recycling the catalyst in an ionic liquid solvent. As separation of the catalyst from products has notoriously been an issue for salen-metal based catalysis,[56] the use of an ionic liquid could potentially facilitate simple removal of products. This could be achieved by simple extraction of products from the IL layer, leaving the highly soluble catalyst, **5a,5b**, behind for reuse.

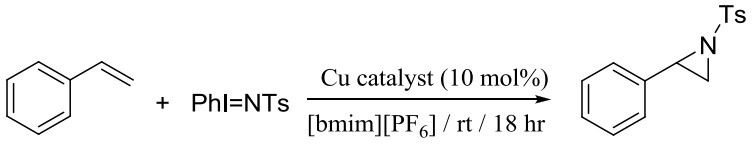


Figure 29. Reaction scheme for the aziridination of styrene using Cu(II) catalysts, **5a,5b**.

Initial reactions were performed using the common ionic liquid, 1-butyl-3-methylimidazolium hexafluoridophosphate, [bmim][PF_6]. The synthesized copper catalyst was easily dissolved in this ionic liquid, making it a promising solvent for potential recycling experiments. The aziridination reaction was carried out in this solvent using the previously optimized ratio of 5:1 styrene:PhI=NTs. After reacting for 18 hours at room temperature, the ionic liquid layer was extracted with portions of diethyl ether. The combined extracts were concentrated *in vacuo* to afford an off yellow solid, which was purified by flash chromatography to afford white crystals. The resulting 2-phenyl-1-tosylazirdine product was obtained in a moderate yield of 48% after purification and was characterized by melting point, ^{1}H NMR and ^{13}C NMR spectroscopy. X-ray quality crystals of the aziridine product were obtained by recrystallization of the product in a 4:1 diethyl ether/hexanes mixture (Figure 30).

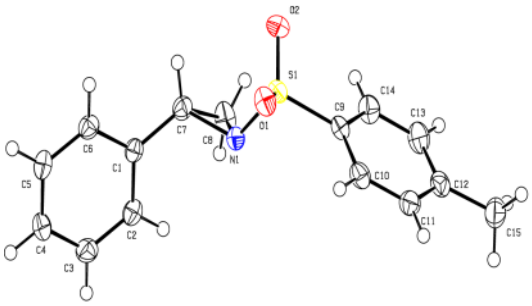


Figure 30. X-ray structure of the 2-phenyl-1-tosylaziridine product.

Although the aziridination reaction carried out in [bmim][PF_6] generated only a moderate yield of 48%, this was still a promising result as previous attempts using an IL-salen-Cu complex in an ionic liquid resulted in very low yields of 19%, or no product formation.[47,48] Once a successful reaction was performed in an ionic liquid, the recyclability of the reaction was investigated to determine if the catalyst would still be catalytically active over additional runs. Prior to successive runs, the IL layer was washed repeatedly with water to ensure complete removal of any undesirable contaminants such as HF, which is a hydrolytic decomposition product of [bmim][PF_6].[57] As the catalyst is highly insoluble in water owing to its hydrophobic nature, the risk of catalyst loss by washing with water is not thought to be an issue, although investigation into potential leaching of the catalyst is still required.

Once the ionic liquid was washed and thoroughly dried, a successive run was performed using the same reaction conditions as in the first run. Subsequent extraction and removal of solvent afforded a similar yellow solid as observed in the first run, and the crude product was purified by flash chromatography (1:10 hexanes/EtOAc). The isolated product was obtained in 44 % yield and its identity was confirmed by ^{1}H NMR and ^{13}C NMR spectroscopy to be 2-phenyl-1-tosylazridine.

Although [bmim][PF_6] was found to be a suitable solvent for recycling of the Cu(II) catalyst, it suffers from several drawbacks. One of the major challenges with [bmim][PF_6] is its high viscosity of 450 cP, which would have negative effects on reactivity due to a lower probability of collisions between reactants.[58] The hydrolytic decomposition of [bmim][PF_6] to form HF in the presence of moisture is a concern as well, which can potentially have negative effects on catalytic activity. To avoid these issues, the ionic liquid 1-butyl-3-methylimidazolium bis(trifluoromethane)sulfonamide, [bmim][$N(Tf)_2$], was investigated as its viscosity is much

lower at 52 cP.[58] The combination of its lower viscosity and inability to hydrolyze to form HF, potentially makes [bmim][$N(Tf)_2$] a more promising solvent for recycling studies than its PF_6 counterpart.

The ionic liquid tagged catalyst, **5a,5b**, was highly soluble in [bmim][$N(Tf)_2$] as well. The aziridination reaction was carried out in this solvent using the previously optimized conditions, which upon extraction and purification afforded the product in an increased isolated yield of 60%. Prior to subsequent recycling reactions, the IL was again washed with water and dried to ensure removal of any unwanted contaminants. The catalyst was found to be catalytically active over several runs, affording consistent isolated yields over three successive trials (Table 3).

Table 3. Aziridination recycling study performed in selected ionic liquids at room temperature.

Run #	Olefin/Nitrene Source (mmol)	IL-Solvent	Yield (%)
1	5:1	[bmim][PF_6]	48
2	5:1	[bmim][PF_6]	44
1	5:1	[bmim][$N(Tf)_2$]	60
2	5:1	[bmim][$N(Tf)_2$]	58
3	5:1	[bmim][$N(Tf)_2$]	62

Although much of this work was directed towards successful recycling of the catalyst over several runs, the ultimate goal is to generate the aziridine product in high enantiomeric excess (ee). This goal of achieving high enantioselectivity helped guide the design of the ligand, **4**, which features bulky tributylphosphonium moieties on the 5 and 5' position of the aryl ring. The rationale of incorporating bulky substituents on the ligand is borne from numerous reports on the directing nature of the 5 and 5' substituents,[25] which have been shown to have substantial

effects on enantioselectivity. This is best explained by considering the possible approaches in which the olefin can interact with the Cu(IV)-NTs complex (Figure 31). Approach "c" is not favored due to the bulky *tert*-butyl groups on the 3,3' position of the salicylaldehyde ring. Similarly, olefin approach through routes "a" and "b" are unfavorable due to the steric bulk accompanying the tributylphosphonium moiety on the 5,5' position. This then leaves "d" as the most favorable approach, which places the approaching olefin in proximity to the stereogenic carbon centers, allowing for more pronounced stereochemical communication between the olefin and complex.[25] Therefore it is expected that a ligand bearing bulky sp^3 hybridized phosphonium moieties will afford higher enantioselectivity compared to previously investigated imidazolium based catalysts.

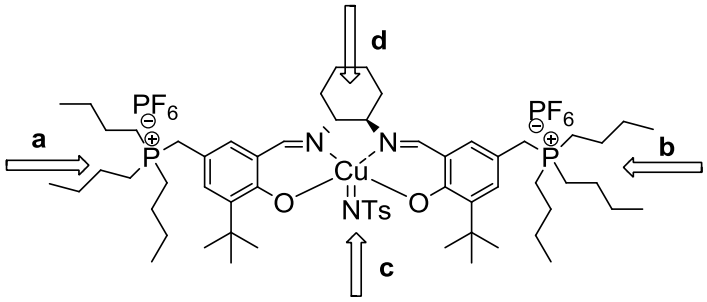


Figure 31. Possible approaches of an olefin towards the active IL-saldach-Cu=NTs complex, **5**.

Once the synthesized aziridine products were fully characterized, they were subjected to chiral LC analysis to determine their enantiomeric excess. The resulting chromatograms of the aziridine samples, which were obtained by using a 99.5% hexane/isopropanol mobile phase, were found to consistently feature two different peaks of different areas, which. The best result obtained was that of the first run in [bmim][$N(Tf)_2$], producing peak areas of 41.9% and 59.1% respectively, which would correspond to an ee of 18.2% (Figure 32). Unfortunately, as no baseline to baseline resolution could be achieved for the chiral LC analysis, it was not possible to obtain an accurate measure of the submitted samples ee values. To rectify this problem in future

experiments, other methods for determining the ee of the samples will be explored, such as polarimetry studies or derivatization techniques.[58]

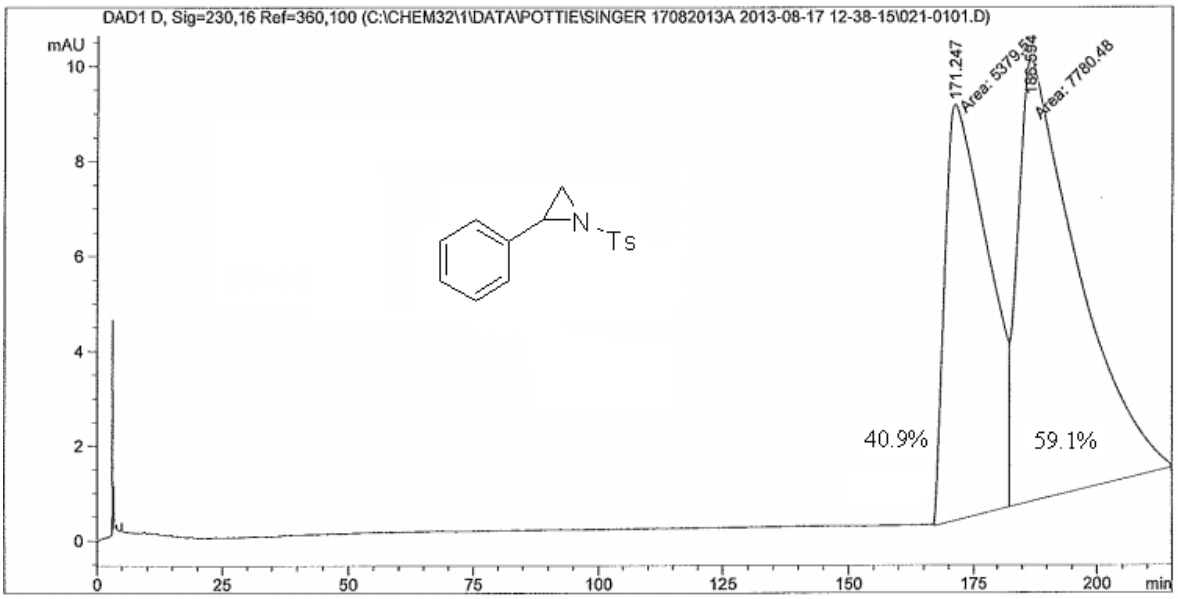


Figure 32. Chiral LC chromatogram of an aziridine product.

2.2.2 Epoxidations

In order to demonstrate the ability to use IL-salen complexes in biphasic catalysis, the ligand, **4a,4b**, was used to prepare Mn(III) complexes, **6a,6b**, which would be used to catalyze the epoxidation of styrene (Figure 33). This complex was easily dissolved in both [bmim][PF_6] and [bmim][$N(Tf)_2$], making their use in recycling studies a promising endeavour. Once the catalyst had been dissolved in the IL, the oxidant was introduced, followed by addition of the substrate. After reacting for two hours at room temperature, the styrene oxide product was extracted with portions of n-hexane and the conversion was determined *via* ^{1}H NMR spectroscopy. Previous work on epoxidations done by Naik[46] featured the use of iodosobenzene

as the oxidant. However as it is relatively expensive and insoluble in both water and typical extracting solvents, the cheaper oxidant NaOCl was chosen for this work.

In order to optimize reaction conditions, several experimental variables were investigated, most notably the stoichiometry of the olefin and oxygen source. Although a 5:1 ratio of olefin to nitrene source was found to be the optimal stoichiometry for the aziridination reaction, this limits the application of the method, as the alkene reactant would most likely be more valuable than the nitrene source. Also by using an excess of reactant, this goes against the principles of green chemistry, mainly waste reduction, which is one of the aims of this work.

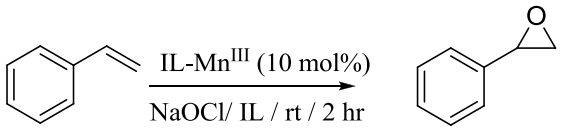


Figure 33. Reaction scheme for the epoxidation of styrene using Mn(III) catalysts, **6.**

Fortunately, it was found that a 5:1 oxidant to styrene ratio was the optimum stoichiometry for the epoxidation, yielding 100% conversion of styrene into styrene oxide, as determined by ^{1}H NMR (Table 4). The conversion percentages were calculated based on the relative integrations of the styrene proton appearing at 6.7 ppm in $CDCl_3$ and the styrene oxide proton appearing at 3.8 ppm in $CDCl_3$. To prepare the NMR samples, a small portion of n-hexane was allowed to stir atop the IL reaction layer, followed by extraction of a small aliquot of organic solution, which was dissolved in deuterated chloroform and analyzed by ^{1}H NMR spectroscopy.

Table 4. Optimization of stoichiometry for epoxidation reactions conducted in [bmim][$N(Tf)_2$] at room temperature for 2 hours

Styrene (mmol)	Oxidant (mmol)	Conversion (%)
5	1	34
1	1	21
1	5	100

Once the optimal stoichiometry had been established, the catalyst loading was investigated to see if full conversion could also be obtained for reactions carried out using less than 10 mol% (Table 5). The catalyst loading was varied between 5-10 mol% and it was found that lowering the catalyst loading to 8 mol% still allowed for quantitative conversion of substrate. Though this represents only a small reduction in catalyst mass for small scale reactions such as the ones featured in this study, extending this work to industrial applications becomes increasingly more viable as catalyst loadings are reduced.

Table 5. Optimization of catalyst loading for the epoxidation reaction in an ionic liquid.

Styrene/Oxidant (mmol)	Catalyst Loading (mol %)	Conversion (%)
1:5	10	100
1:5	8	100
1:5	5	57
1:5	0	0

With the stoichiometry and catalyst loading optimized, the goal was then to see if complex **6a,6b**, would remain catalytically active over successive runs. The recyclability of the catalyst was tested in both [bmim][PF_6] and [bmim][$N(Tf)_2$], as both were found to be suitable

solvents for the recycling of the analogous copper (II) catalyst. Prior to recycling experiments, the IL layer was washed with portions of water and thoroughly dried. The second run was carried out in the same fashion as the first, with a small portion of n-hexane being used to extract the product for ^{1}H NMR analysis (Table 6). It was found that 76% and 69% conversion were obtained for the second run in [bmim][PF_6] and [bmim][$N(Tf)_2$] respectively. A third run was performed in each IL, however numerous impurities appeared in the corresponding ^{1}H NMR spectrum, preventing the conversion from being measured. Future experiments will be aimed at ensuring the IL is of high purity and dryness prior to successive runs, in hopes of allowing for product conversion to be observed over more runs.

Table 6. Epoxidation recycling study performed in selected ionic liquids using previously optimized conditions.

Run #	**Olefin/Oxidant (mmol)**	**IL-Solvent**	**Conversion (%)**
1	1:5	[bmim][PF_6]	100
2	1:5	[bmim][PF_6]	69
1	1:5	[bmim][$N(Tf)_2$]	100
2	1:5	[bmim][$N(Tf)_2$]	76

3.0 Conclusion

Both the racemic and asymmetric ligands, **4a,4b**, were successfully synthesized in high yields of 86% and 90% respectively. The ligands, **4a,4b**, were successfully chelated to both copper and manganese, and the corresponding complexes were fully characterized, with an X-ray structure of the manganese catalyst, **6b-**$(EtOH)_2$, being obtained. The resulting complexes were found to be catalytically active in aziridination and epoxidation reactions in several ionic liquids. The Cu (II) catalyst was able to be recycled two times in [bmim][PF_6] and three times in [bmim][$N(Tf)_2$] IL's without appreciable loss in product yield over successive runs. Preliminary chiral LC analysis indicates the copper(II) catalyst, **5b**, is in fact enantioselective; however further optimization of the chiral HPLC conditions are required to gain an accurate measure of their ee values.

The manganese (III) complex, **6**, was found to successfully catalyze the epoxidation of styrene in both [bmim][PF_6] and [bmim][$N(Tf)_2$], achieving full conversion of styrene into styrene oxide under optimized conditions. The catalyst loading was investigated as part of the optimization study and it was found that full conversion could be obtained using a reduced loading of 8 mol%. The manganese complex was successfully recycled in the epoxidation reaction in both [bmim][PF_6] and [bmim][$N(Tf)_2$], achieving full to moderate conversion (76%) over two runs, however more efficient protocols are required to obtain high conversion over a higher number of runs.

4.0 Future Work

Successful recycling of the manganese epoxidation catalyst, **6**, over multiple runs while obtaining high conversion still needs to be completed. Ensuring both the catalyst and IL is of high purity prior to successive runs is potentially a solution for this. As the X-ray structure for **6** did not match the expected structure, further investigation is required to determine if the true species is in fact a $Mn(salen)^+$ cationic complex.

The ability of complexes, **5** and **6**, to catalyze the reactions using other alkene substrates still requires investigation. Typical olefins used in aziridinations and epoxidations such as 6-cyano-2,2-dimethylchromene, indene and 1,2-dihydronapthalene should be investigated in order to establish the scope and limitations of these systems.

To investigate the enantioselectivity of the copper and manganese catalysts, all catalytic products should be analyzed in order to determine their enantiomeric excesses.

Further inquiry into the recyclability of the catalysts working in an ionic liquid should be investigated as well to determine if they will remain catalytically active for up to five to ten runs. The calculation of turnover frequencies (TOFs) and turnover numbers (TONs) should also be performed as both are very useful in characterizing efficiency of a given catalytic system.

Leaching of the catalyst is a concern in any catalytic system, as such investigation into the potential of the copper and manganese complexes to leach into the extracting solvent should be performed. This can be achieved by ICP-MS whereby an aliquot of the extracting solvent can be analyzed by using a standard to determine the manganese and copper content present in solution.

Once the enantiomeric excesses of the catalyzed products are determined, modification to the ligand design may require investigation, as substituents at the 3,3’ and 5,5’ positions are known to have marked effects on enantioselectivity for these systems.

5.0 Experimental

5.1 General Procedure

The synthesis of the metal complexes and subsequent aziridination and epoxidation reactions were carried out in glassware that was washed with water, soap, and acetone before being left to dry in an oven at 115°C. Glassware used in the aziridination and epoxidation reactions were cooled under vacuum, and flushed with nitrogen before use. Chemical and deuterated solvents were purchased from Sigma-Aldrich and were used without further purification. Dry toluene was obtained from an Innovative Technology solvent system where the solvent was stored in a dry round bottom flask containing 4Å molecular sieves. Ionic liquids, [bmim][PF_6] and [bmim][$N(Tf)_2$] were synthesized in accordance with literature procedures[48], and were stored and dried prior to use. Column chromatography was conducted using 230-400 silica gel mesh and was monitored by TLC using a UV-lamp to visualize the plates.

Manganese (II) acetate tetrahydrate was purchased from Sigma-Aldrich, and copper (II) acetate monohydrate was purchased from Fischer Chemicals. 3-*tert*-Butyl-2-hydroxybenzaldehyde, paraformaldehyde, tetra-butylammonium iodide, tri-n-butylphosphine, hexafluoridophosphoric acid (65% w/w), *trans*-1,2-diaminocyclohexane, (1*R*,2*R*)-(−)-1,2-diaminocyclohexane (99% ee), *para*-toluenesulfonamide, potassium hydroxide, diacetoxyiodobenzene, sodium hypochlorite (10-15% w/v), and styrene were purchased from Sigma-Aldrich. Sodium bicarbonate, sodium chloride, and sodium bisulfite solutions used in the extraction and purification of **1,** were also purchased from Sigma-Aldrich.

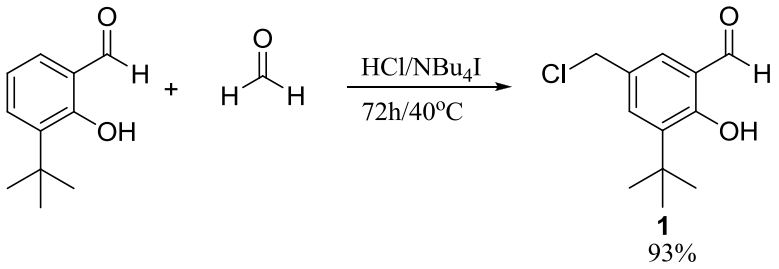
Nuclear magnetic resonance spectroscopy (NMR) was conducted both at the Nuclear Magnetic Resonance Research Resource (NMR^3) at Dalhousie University, and at Saint Mary's

University. All NMR spectra were obtained using a Bruker AV 300 MHz and a Bruker AV 500 MHz Spectrometer using TopSpin 1.3 software.

Infrared (IR) spectra were recorded as KBr pellets using a Bruker Vertex 2.2 Infrared Spectrometer and were processed using OPUS software. Melting points were obtained using an Electrothermal Mel-Temp 3.0 apparatus. Elemental analysis (EA) and electrospray ionization mass spectrometry (ESI-MS) were performed at the Center for Environmental Analysis and Remediation at Saint Mary's University by Patricia Granados. ESI-MS was performed using an Agilent 1100 LC/MSD trap. All high resolution ESI-MS were performed at the Maritime Mass Sprectrometry Laboratory at Dalhousie University using a Bruker microTOF Focus Mass Spectrometer. Elemental analysis was carried out using a Perkin Elmer 2400 Series II CHN Elemental Analyzer.

5.2 Synthesis of IL-saldach-metal complexes, 5,6

Preparation of 3-*tert*-butyl-5-chloromethyl-2-hydroxybenzaldehyde, **1**

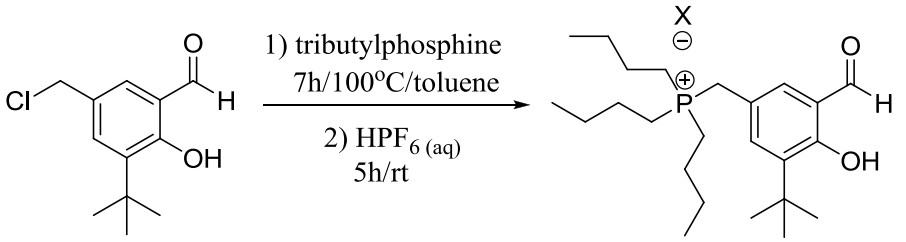


1
93%

Paraformaldehyde (0.6014g, 20.0mmol) was added to ca. 18mL of concentrated hydrochloric acid and left to dissolve. The phase transfer catalyst *t*-butylammonium iodide (0.3648g) was dissolved in the solution, assisted by gentle heating. Once all contents had fully dissolved, 3-*tert*-butyl-2-hydroxybenzaldehyde (1.70mL, 10mmol) was introduced dropwise. The reaction mixture was left to stir at 40°C for 72 hours and resulted in the formation of a dark reddish oil.

The product was obtained via extraction of the aqueous solution with ether (5x10mL). The organic layer was combined and purified by washing with saturated sodium bicarbonate (2x10mL), brine (2x10mL) and sodium bisulfite (3x10mL) to afford a pale yellow solution. The solution was dried with anhydrous magnesium sulphate before removing the solvent via rotary evaporation to afford a yellow solid (2.10g, 93%). m.p. 57.1.-58.6˚C ^{1}H NMR (300 MHz, $CDCl_3$): δ 11.86 (s, 1H), 9.87 (s, 1H), 7.53 (d, ^{4}J=2.27, 1H), 7.44 (d, ^{4}J=2.27, 1H), 4.58 (s, 2H), 1.43 (s, 9H) ppm. ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$) δ 196.75, 161.31, 139.20, 134.56, 131.76, 128.30, 120.36, 45.90, 34.97, 29.12 ppm.

Preparation of tributyl(3-tert-butyl-5-formyl-4-hydroxybenzyl)phosphonium chloride and tributyl(3-*tert*-butyl-5-formyl-4-hydroxybenzyl)phosphonium hexaflurophosphate, **2,3**.

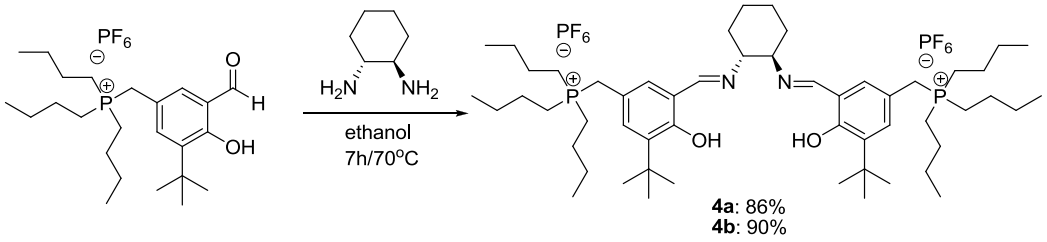


2: Cl, 63% **3**: PF_6, 80%

Compound **1** (1.020g, 4.51 mmol) was dissolved in 25 mL of dry toluene and the resulting solution was stirred under N_2. Tri-n-butylphosphine (1.16mL, 4.64mmol) was dissolved in ca. 5mL of dry toluene under a N_2 atmosphere in a glovebox. The resulting solution was added dropwise *via* syringe to the solution containing compound **1**, turning the solution a faint yellow. The mixture was set to reflux at 100°C for 9 hours. The toluene was then evaporated via rotary evaporation and dried *in vacuo* to afford a sticky yellow solid. Due to its hygroscopic nature, the crude tributyl(3-tert-butyl-5-formyl-4-hydroxybenzyl)phosphonium chloride, **2** (1.255g, 63%), was used in subsequent reactions without characterization.

Compound **2** was dissolved in 40mL of deionized water followed by the slow addition of hexafluoridophosphoric acid (1.61mL, 5.35mmol) *via* syringe. A white precipitate formed immediately, and the solution was left to stir at room temperature for five hours. The white solid was isolated *via* vacuum filtration, and washed with water (3x15mL) before being dried *in vacuo* to afford a white powder (1.261g, 80%). m.p. 151.2-153.6˚C. ^{1}H NMR (300 MHz, $CDCl_3$); δ 11.84 (s, 1H), 9.90 (s, 1H), 7.81 (t, J=2.30Hz, 1H), 7.48 (t, ^{2}J=1.97Hz, 1H), 3.67-3.62 (d, $^{1}J_{P-H}$ =14.94Hz, 2H), 2.14-2.05 (m, 6H), 1.46-1.39 (m, 22H), 0.98-0.93 (t,^{3}J=6.87Hz, 9H). $^{13}C\{^{1}H\}$ NMR (75 MHz, $CDCl_3$): δ 197.21, 161.18, 139.90, 135.34, 133.79, 121.01, 119.43, 119.31, 118.16, 35.10, 29.31, 24.18 (d, $^{1}J_{C-P}$= 15.22Hz), 23.93 ($^{2}J_{C-P}$= 5.01Hz), 19.21, 18.59, 13.54 ppm. $^{31}P\{^{1}H\}$ (121 MHz, $CDCl_3$) δ 31.55 (s), -144.03 (sep, $^{1}J_{P-F}$= 713 Hz) ppm. ESI-MS: Positive mode: m/z 393.3 ($[C_{24}H_{42}O_2P]^+$) Negative mode: m/z 144.6 (100%, $[PF_6]^-$) amu.

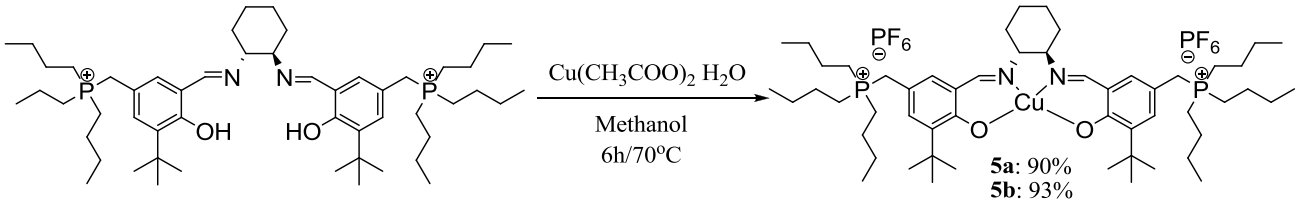
Preparation of racemic and R,R-5,5'-cyclohexane-1,2-diylbis(azan-1-yl-1-ylidene)bis(methan-1-yl-1-ylidene)bis(3-tert-butyl-4-hydroxy-5,1-phenylene)bis(methylene)bis(tributylphosphonium), saldach phosphonium ligand, **4a, 4b**.



Compound **3** (1.845g, 3.42mmol) was dissolved in 40mL of absolute ethanol, assisted by heating at 75°C. An ethanol solution of racemic or R,R-diaminocyclohexane (0.195g, 1.71mmol) was added dropwise to the solution of **3,** resulting in a strong yellow solution. The mixture was left to reflux at 75°C for 7 hours before being left in the freezer overnight to precipitate product. The

product was isolated by vacuum filtration and washed with portions of absolute ethanol to afford a light yellow solid **4a** (1.70g, 86%), **4b** (1.78g, 90%). m.p. 127.3-129.1˚C. ^{1}H (500MHz, $CDCl_3$): δ 14.19 (s, 2H), 8.34 (s, 2H), 7.15 (t, ^{4}J=2.27Hz, 2H), 7.02 (t, ^{4}J=1.81Hz, 2H), 3.74-3.36 (m, 6H), 2.15-1.85 (m, 14H), 1.68-1.23 (m, 48H), 0.85 (t, ^{3}J=7.0Hz, 18H) ppm. ^{13}C{^{1}H} (126 MHz, $CDCl_3$): δ 164.79, 161.31, 160.88, 139.12, 131.08, 130.3712, 119.16, 116.02, 115.95, 69.99, 34.88, 33.38, 29.21, 24.44 (d, $^{1}J_{C-P}$=37.98Hz), 23.85 (d, $^{2}J_{C-P}$=15Hz), 23.24 (d, $^{3}J_{C-P}$=4.79Hz), 18.14 (d, $^{1}J_{C-P}$=47. 95Hz), 13.18 ppm. ^{31}P{^{1}H} (202 MHz, $CDCl_3$): δ 31.17 (s), -144.11 (sep, $^{1}J_{P-F}$= 713 Hz). IR (KBr): 2962, 2937, 2874, 1631, 1594, 1467, 1444, 1387, 1276, 1100, 909, 839 cm^{-1}. ESI MS: Positive mode: m/z 1009.8 ($[C_{54}H_{94}F_6N_2O_2P_3]^+$) Negative mode: m/z 144.6 (100%, $[PF_6]^-$) amu.

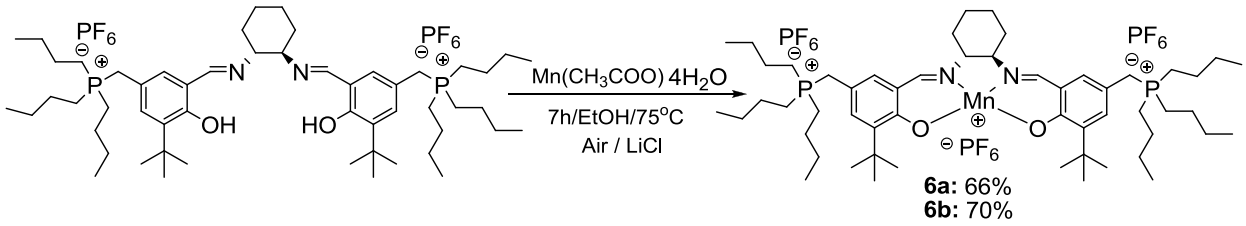
Preparation of racemic and R,R-5,5'-cyclohexane-1,2-diylbis(azan-1-yl-1-ylidene)bis(methan-1-yl-1-ylidene)bis(3-tert-butyl-4-hydroxy-5,1-phenylene)bis(methylene)bis(tributylphosphonium) bis(hexafluoridophosphate) copper (II) complex, saldach phosphonium copper complex, **5a, 5b**.



The previously synthesized compounds **4a,** or **4b** (0.400g, 0.346mmol) were dissolved in 25 mL of methanol, assisted by heating. A methanol solution of cupric acetate monohydrate (0.083g, 0.415mmol) was added dropwise to the solution of **4a,** or **4b,** resulting in a dark purple solution. The mixture was left to reflux at 70°C for 5 hours before being left in the freezer overnight to precipitate out product. The purple precipitate was isolated *via* vacuum filtration and washed with cold methanol (3x5mL) to afford a purple solid **4a** (0.383g, 91%), **4b (**0.391g, 93%) m.p.

decomposed at 300˚C. IR (KBr): 2961, 2873, 1626, 1538, 1465, 1422, 1386, 1351, 1320, 839 cm^{-1}. ESI MS: Positive mode: m/z 1071.3 ($[C_{54}H_{92}CuF_6N_2O_2P_3]^+$) Negative mode: m/z 144.6 (100%, $[PF_6]^-$) amu. HR ESI MS: Positive mode: 462.7939 ($[C_{54}H_{92}CuN_2O_2P_2]^{2+}$) amu. Calculated to be 462.7939 amu.

Preparation of R,R-5,5'-cyclohexane-1,2-diylbis(azan-1-yl-1-ylidene)bis(methan-1-yl-1-ylidene)bis(3-tert-butyl-4-hydroxy-5,1-phenylene)bis(methylene)bis(tributylphosphonium) bis(hexafluoridophosphate) manganese (III) chloride complex, R,R- saldach phosphonium manganese complex,

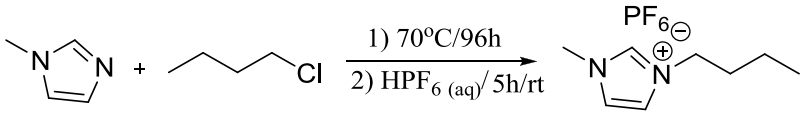


Compound **4a,** or **4b** (0.6940g, 0.6010mmol) was dissolved in ethanol (20mL). Manganese acetate tetrahydrate (0.2968g, 1.21mmol) was also dissolved in ethanol (15mL), which required slight heating. The latter solution was added dropwise to the compound **4a**,**4b**, ethanol solution containing compound **4a,** or **4b** resulting in a dark brown solution. The mixture was refluxed at 75˚C for 5 hours under positive N_2 pressure. The heat was then turned off, and once cooled to room temperature, an ethanol solution of LiCl (0.1528g, 3.604mmol) was introduced and the mixture was left to stir for 2 hours at room temperature. Air was then bubbled into the reaction mixture for 15 minutes and the resulting slurry was placed in the freezer over night, yielding a brown precipitate was isolated by filtration. The resulting brown powder was washed with water (4x25mL) to ensure complete removal of residual acetate and chloride. Compound **6a** (0.614g, 82%), **6b** (0.644g,86%) m.p.199-201°C IR (KBr): 2958, 2936, 2872, 2361, 1656, 1569, 1544,

1421, 1385, 1027, 842.4 cm^{-1}. ESI MS: Positive mode (M/2): m/z 1098.2 ($[C_{54}H_{92}MnClF_6N_2O_2P_3]^+$) Negative mode: m/z 144.6 (100%, $[PF_6]^-$) amu. HR ESI MS: Positive mode: 476.2803 ($[C_{54}H_{92}MnClN_2O_2P_2]^{2+}$) m/z. Calculated to be 476.2852 m/z. EA: 50.88% C, 7.34% H, 2.15% N (Expected: 52.15% C, 7.46% H, 2.25% N).

5.3 Catalytic reactions in an ionic liquid

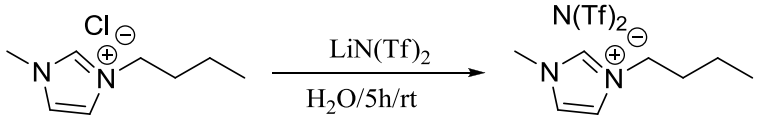
Synthesis of 1-butyl-3-methylimidazolium hexaflouridophosphate, [bmim][PF_6]



Distilled methylimidazolium (42mL, 0.5269mol) and 1-chlorobutane (60.3mL, 0.5796mol) were carefully syringed into a 2-neck round bottom flask while under N_2 atmosphere. The neat yellow mixture was left to stir at 70°C for 96 hours. The resulting off yellow [bmim][Cl] liquid was purified by recrystallization in a 2:1 mixture of ethyl acetate and acetonitrile to afford a white solid crystal (79.2g, 86%). The [bmim][Cl] solid (20.425g, 0.117mol), was dissolved in ca. 50 mLs of water before slow addition of HPF_6 (17.84mL, 0.1287mol) *via* syringe. An off reddish bottom layer was observed immediately upon addition of acid, and the reaction was left to stir for five hours at room temperature. The aqueous layer was removed and the resulting [bmim][PF_6] was washed repeatedly with water (3x25mL), each time performing a silver nitrate test to check for presence of chloride ions. The IL was then dissolved in dichloromethane and decolorizing charcoal was added, left to stir for 30 minutes and then filtered to afford a clear liquid. The solvent was removed and the ionic liquid was dried *in vacuo* to yield a clear, viscous liquid (29.2g, 88%). ^1H (300MHz, $CDCl_3$): δ 10.67 (s, 1H), 7.68-7.66 (t, ^3J=1.81Hz, 1H), 7.52-

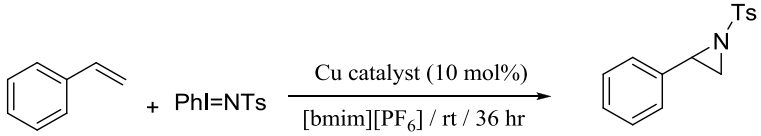
7.51 (t, ^{3}J=1.74Hz, 1H), 4.37-4.34 (t, ^{3}J=7.32Hz, 3H), 4.13 (s, 3H), 1.99-1.86 (m, 2H), 1.45-1.33 (m, 2H), 0.99-0.94 (t, ^{3}J=7.26Hz, 3H).

Synthesis of 1-butyl-3-methylimidazolium bis(trifluoromethane)sulfonimide, [bmim][N(Tf)$_2$]



[bmim][Cl] (18.4g, 0.105mol), was dissolved in ca. 50 mL of water before the addition of an aqueous solution of LiN(Tf)$_2$ (33.3 g, 0.116mol). A clear oil bottom layer was observed immediately upon addition of the lithium salt, and the reaction was left to stir for five hours at room temperature. The aqueous layer was removed and the resulting [bmim][N(Tf)$_2$] was washed repeatedly with water (3x25mL).The IL was then dissolved in dichloromethane and decolorizing charcoal was added, left to stir for 30 minutes and then filtered to afford a clear liquid. The solvent was removed and the ionic liquid was dried *in vacuo* to yield a clear, viscous liquid (37.9g, 86%). ^{1}H (300MHz, $CDCl_3$): δ 9.1 (s, 1H), 7.75-7.74 (t, ^{3}J=1.8Hz, 1H), 7.69-7.67 (t, ^{3}J=1.74Hz, 1H), 4.19-4.14 (t, ^{3}J=7.17Hz, 3H), 3.86 (s, 3H), 1.83-1.73 (m, 2H), 1.32-1.22 (m, 2H), 0.94-0.89 (t, ^{3}J=7.29Hz, 3H).

Aziridination recycling in [bmim][PF$_6$] with the R,R- Saldach Phosphonium Copper Complex.



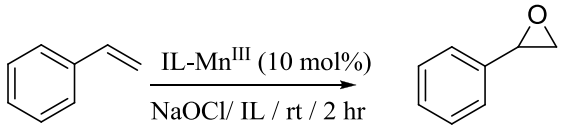
Ca. 3mL of stirred [bmim][PF$_6$] was dried under vacuum in a 50mL 2-neck round bottom for 6 hours while heating at 60°C. Compound **5** (0.1216g, 0.10mmol) was added against a positive pressure of nitrogen and dissolved in the previously dried ionic liquid at room temperature.

PhINTs (0.3728g, 1mmol) was then introduced, followed by addition of styrene (0.55mL, 5.0mmol) *via* syringe. The resulting mixture was stirred for 24 hours and then extracted with 4x8mL of ethyl ether. The ether extracts were combined and removal of solvent afforded an off-yellow solid. The crude product was purified by flash chromatography (hexanes/EtOAc = 10:1) to yield purified 2-phenyl-1-tosylaziridine product as a white solid. Prior to recycling, the IL layer was washed with several portions of water and dried *in vacuo.* See Table 3 for yields. m.p 88-91 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.87 (d, J= 8.3 Hz, 2H),), 7.34-7.19 (m, 7H), 3.77 (dd, J=4.5, 7.2 Hz, 1H), 2.98 (d, J= 7.2 Hz, 1H), 2.43 (s, 3H), 2.38 (d, J= 4.5 Hz, 1H) ppm.

Aziridination Recycling in [bmim][NTf_2] with the R,R- Saldach Phosphonium Copper Complex.

Ca. 3mL of [bmim][PF_6] was dried under vacuum in a 50mL 2-neck round bottom for 6 hours while stirring and heating at 60°C. Compound **5** (0.1216g, 0.10mmol) was added against a positive pressure of nitrogen and dissolved in the previously dried ionic liquid at room temperature. PhINTs (0.3728g, 1mmol) was then introduced, followed by addition of styrene (0.55mL, 5.0mmol) *via* syringe. The resulting mixture was stirred for 24 hours and then extracted with 4x8mL of ethyl ether. The ether extracts were combined and removal of solvent afforded an off-yellow solid. The crude product was purified by flash chromatography (hexanes/EtOAc = 10:1) to yield purified 2-phenyl-1-tosylaziridine product as a white solid. Prior to recycling, the IL layer was washed with several portions of water and dried *in vacuo.* See Table 3 for yields. See Table 8 for crystallographic data. m.p 88-91 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.87 (d, J= 8.3 Hz, 2H), 7.34-7.19 (m, 7H), 3.77 (dd, J=4.5, 7.2 Hz, 1H), 2.98 (d, J= 7.2 Hz, 1H), 2.43 (s, 3H), 2.38 (d, J= 4.5 Hz, 1H) ppm. See appendix for crystal structure data.

Epoxidation Recycling in [bmim][PF_6] with the R,R- Saldach Phosphonium Manganese Complex.



3mL of stirred [bmim][PF_6] was dried under vacuum in a 50mL 2 neck round bottom flask for 6 hours at 60^{o}C. Compound **6** (0.100g, 0.0803mmol) was added against a positive pressure of nitrogen and dissolved in the ionic liquid. NaOCl (2.48mL, 4.015mmol) was then added in one portion followed by styrene (0.092mL, 0.803mmol) being added *via* syringe. The resulting mixture was stirred for 2 hours and then extracted with 4x8mL of n-hexane. To prepare the NMR samples in order to calculate conversions, *n*-hexane was allowed to stir atop the IL reaction layer, followed by extraction of a small aliquot of *n*-hexane, which was dissolved in deuterated chloroform and analyzed by ^{1}H NMR. The organic extracts were combined followed by removal of solvent resulting in an off-yellow liquid. The crude product was purified by flash chromatography (hexanes/EtOAc = 10:1.5, 1% Et_3NH_2) to yield the phenyloxirane product. See Table 6 for conversion percentages. Prior to recycling, the IL layer was washed with several portions of water and dried *in vacuo.* ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.40-7.20 (m, 5H), 3.85-3.83 (dd, J= 2.58, 2.61 Hz, 1H), 3.14-3.11 (dd, J= 4.08, 4.11 Hz, 1H), 2.79-2.75 (dd, J=2.58, 2.58 Hz, 1H).

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7.0 Appendix

Table 7. Selected crystallographic data for compound **6b-**$(EtOH)_2$**.** For full crystallographic data contact the author at chrslavoie@gmail.com

Identification code	CL002	
Empirical formula	C60 H108 F18 Mn N2 O5 P5	
Formula weight	1489.27	
Temperature	125(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	*P*1	
Unit cell dimensions	*a* = 9.386(2) Å	α= 67.776(4)°
	b = 21.873(5) Å	β= 88.233(3)°
	c = 28.899(7) Å	γ = 85.758(3)°
Volume	5478(2) $Å^3$	
Z	3	
Density (calculated)	1.354 Mg/m^3	
Absorption coefficient	0.381 mm^{-1}	
F(000)	2352	
Crystal size	0.270 x 0.200 x 0.140 mm^3	
Theta range for data collection	1.867 to 24.223°	
Index ranges	-10<=h<=10, -25<=k<=23, -33<=l<=10	
Reflections collected	data merged for twin refinement	
Independent reflections	17306 [R(int) = 0.000]	
Completeness to theta = 25.242°	88.6 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.7450 and 0.5506	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	17306 / 2139 / 2468	
Goodness-of-fit on F^2	1.055	
Final R indices [I>2sigma(I)]	R1 = 0.0847, wR2 = 0.2135	
R indices (all data)	R1 = 0.1109, wR2 = 0.2315	
Absolute structure parameter	0.09(3)	
Extinction coefficient	n/a	

Largest diff. peak and hole	1.293 and -0.725 e.Å^{-3}

Table 8. Crystal data and structure refinement for **9.** For full crystallographic data contact the author at chrslavoie@gmail.com

Identification code	2013_07_04_cl01	
Empirical formula	C15 H15 N O2 S	
Formula weight	273.34	
Temperature	127(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P2(1)/c	
Unit cell dimensions	a = 15.452(3) Å	α= 90°.
	b = 7.6786(13) Å	β= 95.285(2)°.
	c = 11.5704(19) Å	γ = 90°.
Volume	1367.0(4) Å^3	
Z	4	
Density (calculated)	1.328 Mg/m^3	
Absorption coefficient	0.234 mm^{-1}	
F(000)	576	
Crystal size	0.42 x 0.21 x 0.18 mm^3	
Theta range for data collection	2.65 to 27.48°.	
Index ranges	-20<=h<=20, -9<=k<=9, -15<=l<=15	
Reflections collected	15311	
Independent reflections	3108 [R(int) = 0.0428]	
Completeness to theta = 27.48°	99.8 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.9592 and 0.9082	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	3108 / 0 / 173	
Goodness-of-fit on F^2	1.041	
Final R indices [I>2sigma(I)]	R1 = 0.0373, wR2 = 0.0870	
R indices (all data)	R1 = 0.0541, wR2 = 0.0954	
Largest diff. peak and hole	0.274 and -0.387 e.Å^{-3}	

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3)
for 2013_07_04_CL01. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
S(1)	7786(1)	1868(1)	6390(1)	24(1)
O(1)	7719(1)	1166(2)	7527(1)	30(1)
O(2)	8216(1)	3514(2)	6298(1)	35(1)
N(1)	6780(1)	1910(2)	5737(1)	22(1)
C(1)	5342(1)	3304(2)	6108(1)	22(1)
C(2)	4790(1)	2242(2)	5400(2)	27(1)
C(3)	3930(1)	2036(2)	5616(2)	29(1)
C(4)	3609(1)	2900(2)	6539(2)	29(1)
C(5)	4153(1)	3959(2)	7250(2)	29(1)
C(6)	5015(1)	4158(2)	7031(1)	26(1)
C(7)	6270(1)	3556(2)	5894(2)	26(1)
C(8)	6620(1)	3178(3)	4775(2)	35(1)
C(9)	8277(1)	321(2)	5541(1)	23(1)
C(10)	8280(1)	-1417(2)	5864(2)	28(1)
C(11)	8682(1)	-2630(2)	5213(2)	31(1)
C(12)	9082(1)	-2134(2)	4234(2)	29(1)
C(13)	9049(1)	-395(3)	3908(2)	34(1)
C(14)	8651(1)	842(2)	4551(2)	31(1)
C(15)	9551(1)	-3461(3)	3561(2)	40(1)

Table 3. Bond lengths [Å] and angles [°] for 2013_07_04_CL01.

S(1)-O(1)	1.4343(12)
S(1)-O(2)	1.4364(13)
S(1)-N(1)	1.6646(14)
S(1)-C(9)	1.7565(17)
N(1)-C(8)	1.483(2)
N(1)-C(7)	1.510(2)
C(1)-C(6)	1.387(2)
C(1)-C(2)	1.391(2)
C(1)-C(7)	1.491(2)
C(2)-C(3)	1.383(2)
C(2)-H(2)	0.9500
C(3)-C(4)	1.387(2)
C(3)-H(3)	0.9500
C(4)-C(5)	1.385(2)
C(4)-H(4)	0.9500
C(5)-C(6)	1.387(2)
C(5)-H(5)	0.9500
C(6)-H(6)	0.9500
C(7)-C(8)	1.477(2)
C(7)-H(7)	1.0000
C(8)-H(8B)	0.9900
C(8)-H(8A)	0.9900
C(9)-C(10)	1.386(2)
C(9)-C(14)	1.389(2)
C(10)-C(11)	1.381(2)
C(10)-H(10)	0.9500
C(11)-C(12)	1.393(3)
C(11)-H(11)	0.9500
C(12)-C(13)	1.387(3)
C(12)-C(15)	1.508(2)
C(13)-C(14)	1.385(3)
C(13)-H(13)	0.9500
C(14)-H(14)	0.9500
C(15)-H(15A)	0.9800

C(15)-H(15B)	0.9800
C(15)-H(15C)	0.9800

O(1)-S(1)-O(2)	118.16(8)
O(1)-S(1)-N(1)	106.26(7)
O(2)-S(1)-N(1)	111.57(8)
O(1)-S(1)-C(9)	109.28(8)
O(2)-S(1)-C(9)	109.11(8)
N(1)-S(1)-C(9)	101.07(7)
C(8)-N(1)-C(7)	59.16(11)
C(8)-N(1)-S(1)	115.95(11)
C(7)-N(1)-S(1)	115.96(11)
C(6)-C(1)-C(2)	118.93(15)
C(6)-C(1)-C(7)	119.36(15)
C(2)-C(1)-C(7)	121.71(15)
C(3)-C(2)-C(1)	120.52(16)
C(3)-C(2)-H(2)	119.7
C(1)-C(2)-H(2)	119.7
C(2)-C(3)-C(4)	120.10(16)
C(2)-C(3)-H(3)	120.0
C(4)-C(3)-H(3)	120.0
C(5)-C(4)-C(3)	119.88(16)
C(5)-C(4)-H(4)	120.1
C(3)-C(4)-H(4)	120.1
C(4)-C(5)-C(6)	119.78(16)
C(4)-C(5)-H(5)	120.1
C(6)-C(5)-H(5)	120.1
C(5)-C(6)-C(1)	120.80(16)
C(5)-C(6)-H(6)	119.6
C(1)-C(6)-H(6)	119.6
C(8)-C(7)-C(1)	123.76(16)
C(8)-C(7)-N(1)	59.52(11)
C(1)-C(7)-N(1)	115.62(13)
C(8)-C(7)-H(7)	115.3
C(1)-C(7)-H(7)	115.3
N(1)-C(7)-H(7)	115.3

C(7)-C(8)-N(1)	61.32(10)
C(7)-C(8)-H(8B)	117.6
N(1)-C(8)-H(8B)	117.6
C(7)-C(8)-H(8A)	117.6
N(1)-C(8)-H(8A)	117.6
H(8B)-C(8)-H(8A)	114.7
C(10)-C(9)-C(14)	120.51(16)
C(10)-C(9)-S(1)	119.45(13)
C(14)-C(9)-S(1)	120.04(13)
C(11)-C(10)-C(9)	119.59(16)
C(11)-C(10)-H(10)	120.2
C(9)-C(10)-H(10)	120.2
C(10)-C(11)-C(12)	120.96(17)
C(10)-C(11)-H(11)	119.5
C(12)-C(11)-H(11)	119.5
C(13)-C(12)-C(11)	118.44(17)
C(13)-C(12)-C(15)	121.19(17)
C(11)-C(12)-C(15)	120.37(17)
C(14)-C(13)-C(12)	121.43(17)
C(14)-C(13)-H(13)	119.3
C(12)-C(13)-H(13)	119.3
C(13)-C(14)-C(9)	119.02(17)
C(13)-C(14)-H(14)	120.5
C(9)-C(14)-H(14)	120.5
C(12)-C(15)-H(15A)	109.5
C(12)-C(15)-H(15B)	109.5
H(15A)-C(15)-H(15B)	109.5
C(12)-C(15)-H(15C)	109.5
H(15A)-C(15)-H(15C)	109.5
H(15B)-C(15)-H(15C)	109.5

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for 2013_07_04_CL01. The anisotropic
displacement factor exponent takes the form: $-2\pi^2[h^2 a^{*2} U^{11} + ... + 2 h k a^* b^* U^{12}]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
S(1)	20(1)	27(1)	25(1)	0(1)	3(1)	-2(1)
O(1)	27(1)	42(1)	21(1)	2(1)	2(1)	2(1)
O(2)	28(1)	30(1)	47(1)	-5(1)	9(1)	-9(1)
N(1)	21(1)	24(1)	23(1)	0(1)	2(1)	2(1)
C(1)	24(1)	20(1)	23(1)	3(1)	2(1)	4(1)
C(2)	31(1)	27(1)	23(1)	-3(1)	3(1)	4(1)
C(3)	28(1)	28(1)	30(1)	-3(1)	-5(1)	1(1)
C(4)	22(1)	33(1)	31(1)	3(1)	3(1)	5(1)
C(5)	30(1)	31(1)	25(1)	-1(1)	6(1)	9(1)
C(6)	29(1)	25(1)	24(1)	-2(1)	-1(1)	3(1)
C(7)	28(1)	19(1)	33(1)	3(1)	6(1)	2(1)
C(8)	30(1)	44(1)	30(1)	14(1)	7(1)	10(1)
C(9)	17(1)	28(1)	24(1)	3(1)	2(1)	0(1)
C(10)	25(1)	32(1)	29(1)	7(1)	6(1)	0(1)
C(11)	26(1)	26(1)	41(1)	2(1)	1(1)	1(1)
C(12)	19(1)	38(1)	30(1)	-5(1)	-2(1)	2(1)
C(13)	33(1)	44(1)	28(1)	5(1)	10(1)	3(1)
C(14)	31(1)	31(1)	30(1)	9(1)	8(1)	2(1)
C(15)	30(1)	47(1)	44(1)	-14(1)	0(1)	7(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for 2013_07_04_CL01.

	x	y	z	U(eq)
H(2)	5005	1654	4763	33
H(3)	3559	1302	5131	35
H(4)	3018	2765	6683	34
H(5)	3936	4548	7886	34
H(6)	5386	4889	7519	31
H(7)	6586	4479	6375	32
H(8B)	7119	3883	4565	42
H(8A)	6202	2845	4112	42
H(10)	8008	-1771	6529	34
H(11)	8686	-3821	5437	37
H(13)	9304	-45	3229	41
H(14)	8635	2029	4319	37
H(15A)	9661	-2974	2805	61
H(15B)	9192	-4510	3444	61
H(15C)	10105	-3763	3996	61

Table 6. Torsion angles [°] for 2013_07_04_CL01.

O(1)-S(1)-N(1)-C(8)	156.54(12)
O(2)-S(1)-N(1)-C(8)	26.44(14)
C(9)-S(1)-N(1)-C(8)	-89.41(13)
O(1)-S(1)-N(1)-C(7)	89.94(12)
O(2)-S(1)-N(1)-C(7)	-40.15(13)
C(9)-S(1)-N(1)-C(7)	-156.01(11)
C(6)-C(1)-C(2)-C(3)	-0.3(2)
C(7)-C(1)-C(2)-C(3)	-179.75(16)
C(1)-C(2)-C(3)-C(4)	0.4(3)
C(2)-C(3)-C(4)-C(5)	-0.5(3)
C(3)-C(4)-C(5)-C(6)	0.3(3)
C(4)-C(5)-C(6)-C(1)	-0.2(3)
C(2)-C(1)-C(6)-C(5)	0.2(2)
C(7)-C(1)-C(6)-C(5)	179.64(15)
C(6)-C(1)-C(7)-C(8)	-160.60(16)
C(2)-C(1)-C(7)-C(8)	18.8(2)
C(6)-C(1)-C(7)-N(1)	130.26(16)
C(2)-C(1)-C(7)-N(1)	-50.3(2)
S(1)-N(1)-C(7)-C(8)	106.03(14)
C(8)-N(1)-C(7)-C(1)	115.65(18)
S(1)-N(1)-C(7)-C(1)	-138.32(13)
C(1)-C(7)-C(8)-N(1)	-102.13(17)
S(1)-N(1)-C(8)-C(7)	-106.05(13)
O(1)-S(1)-C(9)-C(10)	19.94(16)
O(2)-S(1)-C(9)-C(10)	150.52(13)
N(1)-S(1)-C(9)-C(10)	-91.82(14)
O(1)-S(1)-C(9)-C(14)	-160.46(14)
O(2)-S(1)-C(9)-C(14)	-29.88(16)
N(1)-S(1)-C(9)-C(14)	87.78(15)
C(14)-C(9)-C(10)-C(11)	1.9(3)
S(1)-C(9)-C(10)-C(11)	-178.55(13)
C(9)-C(10)-C(11)-C(12)	-0.2(3)
C(10)-C(11)-C(12)-C(13)	-1.6(3)
C(10)-C(11)-C(12)-C(15)	177.40(16)

C(11)-C(12)-C(13)-C(14)	1.8(3)
C(15)-C(12)-C(13)-C(14)	-177.16(17)
C(12)-C(13)-C(14)-C(9)	-0.2(3)
C(10)-C(9)-C(14)-C(13)	-1.6(3)
S(1)-C(9)-C(14)-C(13)	178.77(14)

Symmetry transformations used to generate equivalent atoms: