Ferrocenylimidazolium Salts: Their Potential use as Lewis Acids and Anion Receptors.

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Submitted as the Requirement for the Degree of M.Sc.

At Dublin City University, School of Chemical Sciences under the
Supervision of Dr. Joshua Howarth

September 2000

DECLARATION

I hereby certify that this material, which I now submit on the programme of study leading to the award of M.Sc., is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: Damien McGuirk I.D. No. 96971410

Damien McGuirk.

Date: 15 · 8 · 2000

CONTENTS

ABBREVIATIONS

Anal.	Analysis
atm.	Atmosphere
Aq.	Aqueous
Ar	Aryl
b.p.	Boiling point
Bu	Butyl
n-Bu	*normal*-Butyl
Calcd	Calculated
Cat.	Catalyst
Cp	Cyclopentadienyl
conc.	Concentrated
E	Electrophile
Et	Ethyl
n-Et	*normal*-Ethyl
Et_2O	Diethyl ether
EtOH	Ethanol
Et_3N	Triethylamine
equiv.	Equivalent
Fc	Ferrocenyl
h	Hour
Hz	Hertz
Im	Imidazole
I.R.	Infra-red Spectroscopy
KO^{t}Bu	Potassium *tert*-Butoxide
L	Ligand
L.A.	Lewis Acid
lit.	Literature Value
M	Metal
Me	Methyl
n-Me	*normal*-Methyl

mol.	Mole
MPFA	2-(Dimethylphosphinoferrocenyl) ethyldimethylamine
NaOEt	Sodium Ethoxide
NMR	Nuclear Magnetic Resonance Spectroscopy
Ph	Phenyl
PPFA	2-(Diphenylphosphinoferrocenyl) ethyldimethylamine
Pr	Propyl
n-Pr	*normal*-Propyl
Rxn. Temp.	Reaction Temperature
THF	Tetrahydrofuran
TLC	Thin Layer Chromatography
v/v	Volume per Volume

PUBLICATIONS

The following papers were published as part of the work contained in this thesis:

J. Howarth, J.L. Thomas, and D. McGuirk, *Synth. Comm.*, **2000**, *30(10)*, 1865.

J.L. Thomas, J. Howarth, K. Hanlon, and D. McGuirk, *Tetrahedron Lett.*, **2000**, *51-3*, 413.

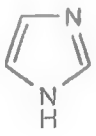
For Willie and Rosarii

CHAPTER 1

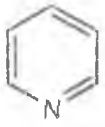
SURVEY OF THE LITERATURE

1.1 Imidazoles

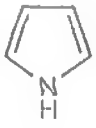
Imidazole **(1)** was first discovered in 1858 by DeBus who prepared this important nitrogen heterocycle from glyoxal and ammonia.[1] To indicate its source, DeBus proposed the name glyoxaline but it was not until 1888 that Hantzcsh[2] named the compound as imidazole. The term imidazole implies a five membered, planar heterocyclic ring system containing three carbons and two nitrogen atoms in the 1- and 3-positions. The systematic name for the compound is then 1,3-diazole. One of the annular nitrogens, N-1, bears a hydrogen atom similar to that found in pyrrole **(3)**, the other nitrogen, N-3, resembles the nitrogen found in pyridine **(2)**. The molecule is aromatic in character *via* a contribution of one π electron from each annular carbon and the 'pyridine' nitrogen, and two from the 'pyrrole' nitrogen to make up the aromatic sextet. The aromaticity of imidazole and its derivatives can be inferred from the appearance of their ^{1}H NMR spectra in which the imidazolium proton signals are down field (δ = 7.2-7.7 ppm). It is for these reasons that it is possible to look upon imidazole as a molecule, which has overlapping properties of both pyrrole and pyridine.



(1)



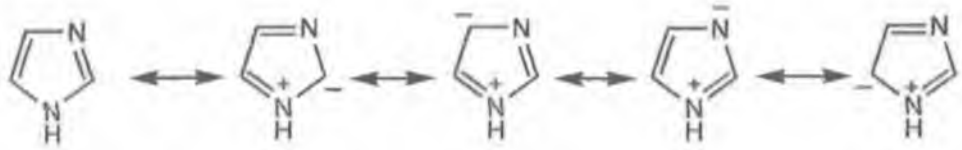
(2)



(3)

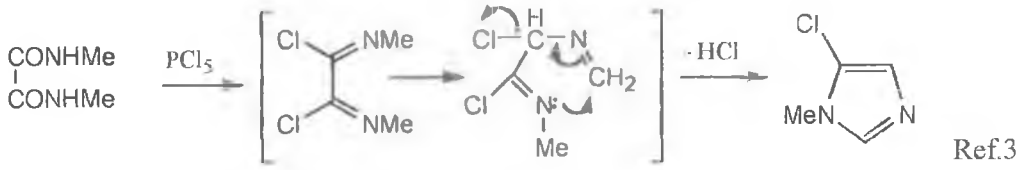
The above structure for imidazole is not sufficient in accounting for the actual dimensions of the molecule, nor for its reactivity and physical properties hence a mesomeric structure **(4)** or a set of resonance structures are necessary to fully describe the ring as shown in Scheme 1.

(4)



Scheme 1

There are many routes available for the synthesis of the imidazole ring, but a variety of reactions, particularly cyclization reactions, are employed to produce specifically substituted imidazoles. In general, imidazole ring syntheses can entail the formation of between one and four bonds from largely acyclical precursors to effect ring closure. A few well known examples of these syntheses are given below in Scheme 2.



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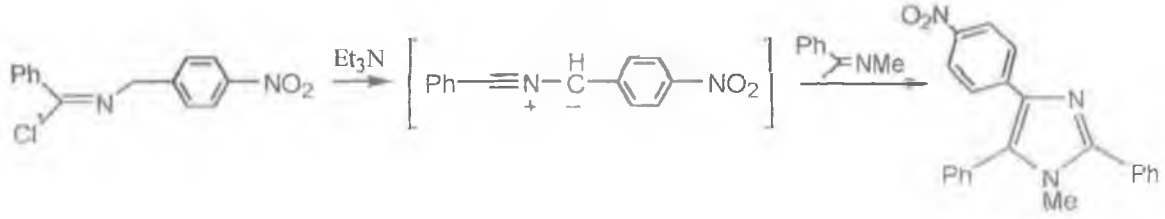
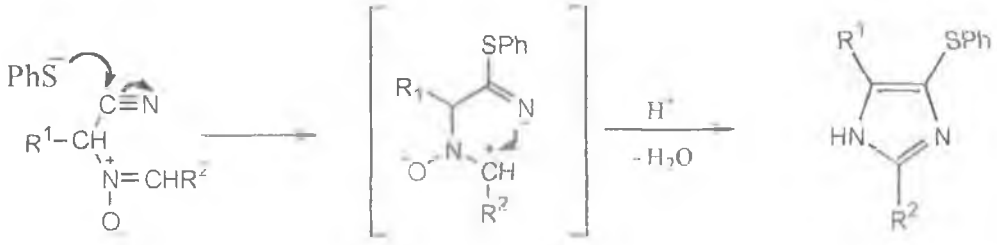


Ref. 4



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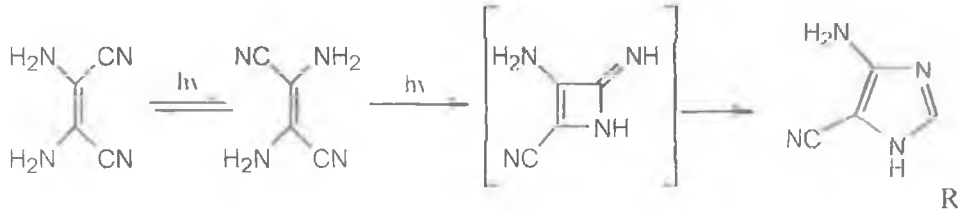


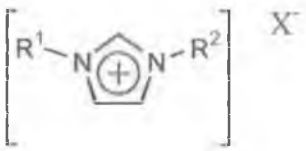
Ref. 6

Scheme 2

1.2 Synthetic Methods for 1,3 Disubstituted Imidazolium salts

1.2.1 Quaternization Reactions

Imidazoles undergo quaternization reactions, which give rise to 1,3-disubstituted imidazolium salts of the following general formula **(6)**.



R = Alkyl/Aryl group
X = Counter anion.

(6)

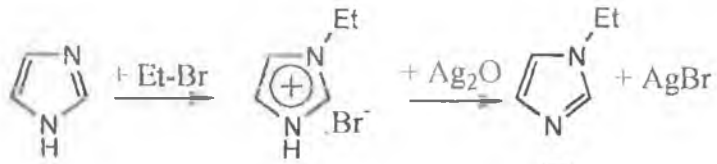
Quaternization of an annular nitrogen atom occurs when its lone pair of electrons is not involved in the formation of σ or π bonding orbitals prior to reaction. These electrons may form a bond between that nitrogen atom and the carbon atom of a halide reagent RX of suitable polarisability, which results in the nitrogen atom becoming quaternary.

The reaction may be visualised as a pure S_N2 process *i.e.* bimolecular nucleophilic replacement of a halogen or similar leaving group, by attack of the electron pair of the heterocyclic nitrogen as in Scheme 4.

Scheme 4

As the quaternization reaction is S_N2 in character it will also be influenced by other substituents present on the ring, steric factors, solvent factors, and the nature of the group R.[8]

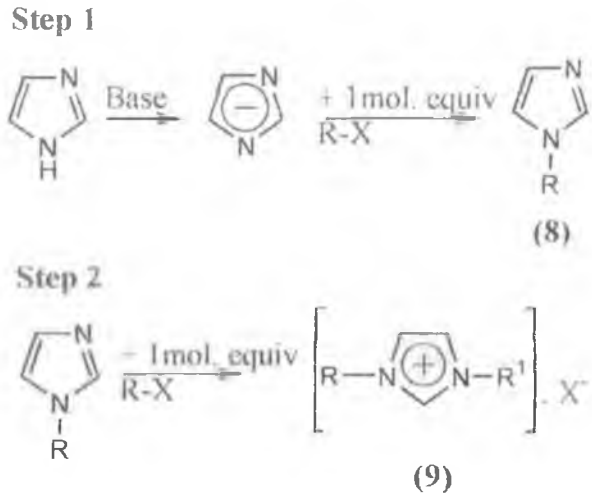
Quaternization of imidazole derivatives was first observed by Wyss[9] in 1877 who prepared 1-ethylimidazole *via* quaternization of imidazole with 1-bromoethane to form the 1-ethylimidazolium bromide intermediate. Further treatment of this intermediate salt with silver oxide gave 1-ethylimidazole **(7)** (Scheme 5).



Scheme 5

1.2.1.1 Organohalides

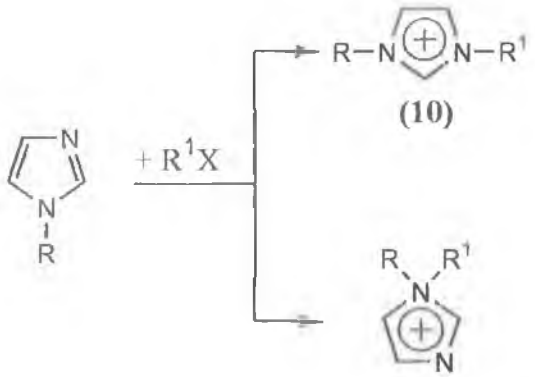
The reaction between imidazole derivatives and alkyl or aryl halides is one of the most widely used synthetic methods for producing 1,3-disubstituted imidazolium salts. Conventional n-alkylimidazole precursors can be prepared by alkylation of the imidazole anion, which is generated by first reacting the imidazole with a suitable base such as sodium, sodium/potassium hydroxide, sodium/potassium carbonate, sodium hydride or sodium ethoxide.[10] The N-1 nitrogen is consequentially de-protonated to yield a resonance stabilised imidazolium anion, which then attacks the organohalide to yield the 1-alkylimidazole derivative **(8).** The 1-alkylimidazole derivative can then be reacted with another equivalent of the alkylating agent to yield the quaternized imidazolium salt derivative **(9)** (Scheme 6).



Scheme 6

Because the quaternization steps in this scheme are in two steps, it is possible to vary the alkyl chain lengths on N-1 and N-3 of the imidazolium salt by this route by using a different organohalide in step 2.[11]

Initially, the formation of 1,3-dialkylimidazolium salt derivatives was thought to occur in two ways. Either the alkyl halide adds to the non-alkylated nitrogen N-3 to form the 1,3-dialkylimidazolium salt **(10)** or it may combine with the substituted nitrogen N-1 to form a 1,1-dialkylimidazolium salt **(11)** (Scheme 7).



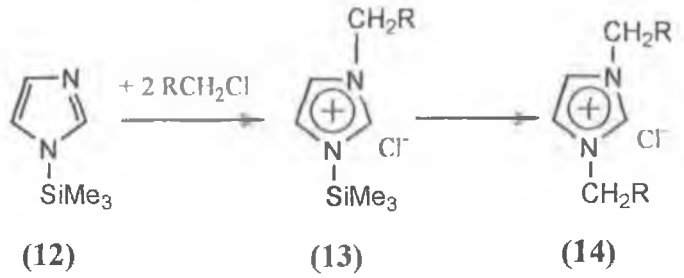
Scheme 7

Investigations carried out by Piner and Schwarz in 1902[12] concluded that the early disubstituted imidazolium salts behaved as 1,3-derivatives and not 1,1-derivatives.

It should be noted however that other halogenated compounds have been used in this synthetic route *ie.* organohalides of alkenes, alkynes, alkyl and aryl chloromethyl ethers.[13]

1.2.1.2 Use of n-Trimethylsilylimidazole

A one-pot synthetic route for symmetrical 1,3–imidazolium salts was developed by Harlow *et al.*[14] The route involved the reaction of commercially available n-trimethylsilylimidazole **(12)** with two equivalents of an alkyl or aryl halide to form the quaternary imidazolium salt **(14)**. The reaction was presumed to proceed *via* a n-trimethylsilyl n'-alkylimidazolium salt intermediate **(13)** which was generated *in situ*. This intermediate was prone to halo-desilylation by the second equivalent of organohalide reagent, to provide the imidazolium salt. The reaction was typically carried out under reflux in anhydrous toluene (Scheme 8).



(12) **(13)** **(14)**

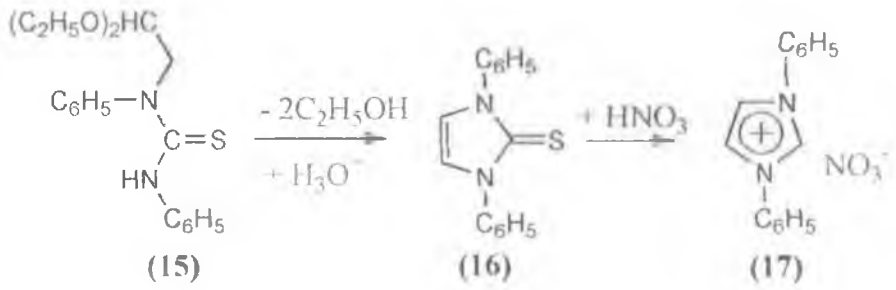
Scheme 8

1.2.2 Ring Condensation Routes

In these reactions, the imidazole ring is first formed from a suitable intermediate or intermediates by the formation of three or four bonds, followed by subsequent elimination to create the positively charged imidazolium ring.

1.2.2.1 Desulfurisation of Imidazole-2-Thiones

This multi-step route was used by Wanzlick and Schonherr in 1968.[15] Equi-molar amounts of n-(2,2-diethoxyethyl) aniline and phenyl isothiocyanate were mixed for a perjod of four days at room temperature to yield the thiourea derivative **(15)** which was treated with acid to yield n,n-diethylimidazole-2-thione **(16)**. On desulfurisation of the thione with 36% v/v nitric acid, the n,n-dialkylimidazolium salt **(17)** was formed (Scheme 9).



(15) **(16)** **(17)**

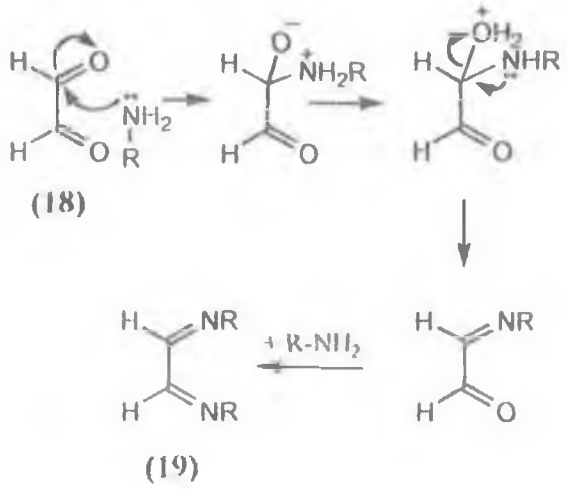
Scheme 9

The drawback of this synthetic route was that it required several steps to synthesise the desired imidazole-2-thione precursor.

1.2.2.2 Condensation of α-Dicarbonyls and *bis*-Imines

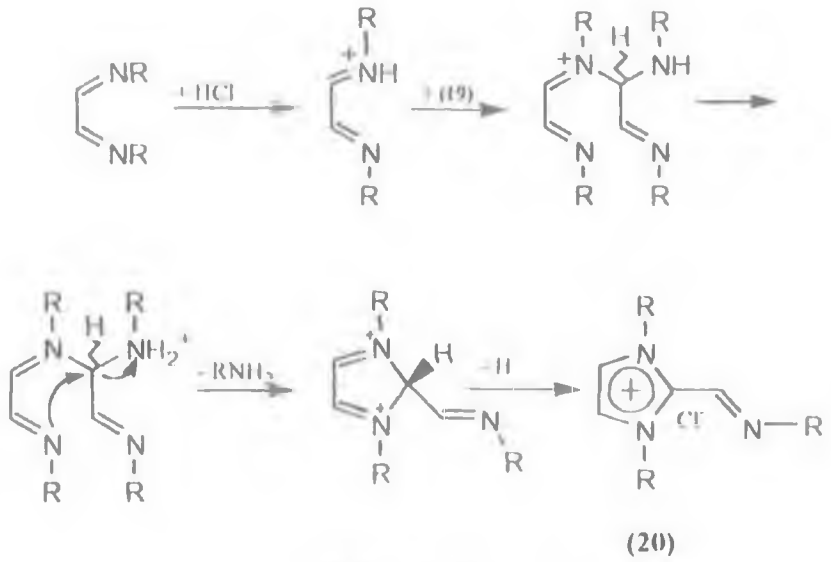
M.Zettlitzer *et al.*[16] utilised the route for the synthesis of n,n'-dialkylimidazolium salts from glyoxal and alkylamines.

The initial step of this route involves the reaction of the α-dicarbonyl compound glyoxal **(18)**, with two mole equivalents of an appropriate alkylamine to produce a diazadiene or diimine compound **(19)** by the following mechanism illustrated in Scheme 10.



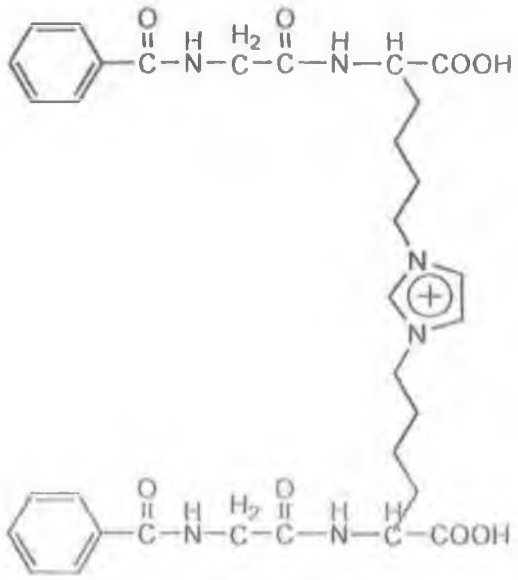
Scheme 10

In the second step, the diimine reacts with dry hydrogen chloride in a nonaqueous solvent system to form the imidazolium salt **(20)** (Scheme 11).



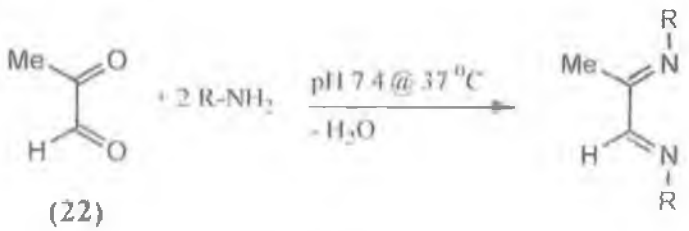
Scheme 11

Brinkmann and co-workers[17] reported a similar synthetic route when studying the Maillard reaction, a reaction which occurs in biochemical pathways between reducing sugars and amino groups on proteins. Brinkmann's research group hypothesised that the cross-linkage of proteins in this reaction was due to the formation of a 1,3-disubstituted imidazolium moiety *via* the reaction between α-dicarbonyls and the amino groups of proteins. This reaction could give rise to structures such as the 1,3-bis-n α –hippuryl-lysine-imidazolium salt **(21)**.



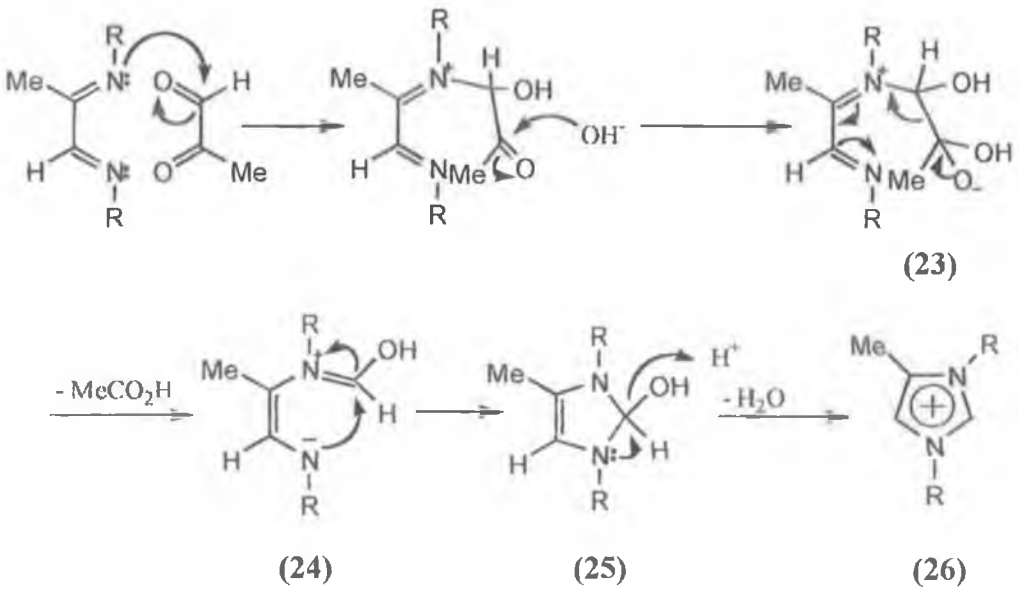
(21)

A test reaction[18] was carried out by stirring two equivalents of methyl glyoxal **(22)** and an amino acid for 3 days in phosphate buffer at pH = 7.4, to yield the imidazolium salt **(26)** by the following mechanism shown in scheme 12.



(22)

Scheme 12



(23)

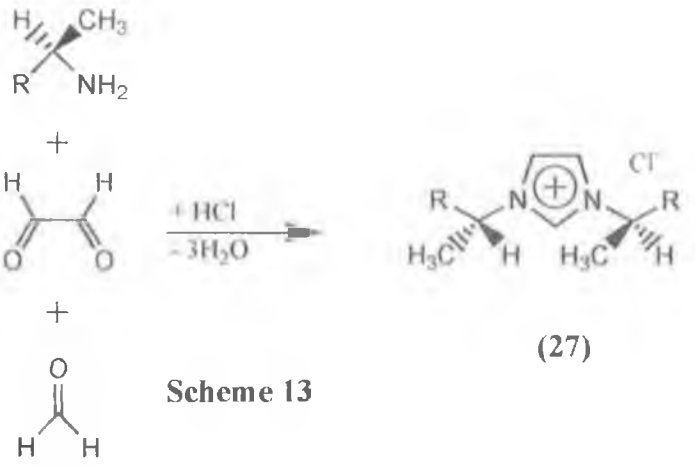
(24) **(25)** **(26)**

Scheme 12 cont'd.

Acetic acid is eliminated in an intramolecular Canizzaro-type reaction *via* intermediates **(23)** and **(24)**, forming **(25)** which undergoes dehydration to form the imidazolium salt. The attractiveness of the above route lies in the possibility of synthesising imidazolium salts in relatively mild conditions using aqueous solvent systems and near neutral pH medium.

1.2.2.3 Chiral 1,3-Disubstituted Imidazolium Salts

As a further expansion of the synthetic method discussed in Section 1.2.2.2., a method for the synthesis of chiral 1,3-disubstituted imidazolium salts **(27)** patented by Arduengo was released.[19] This route involved a condensation reaction between glyoxal, formaldehyde and a chiral amine in the presence of a strong acid, such as hydrochloric acid, as shown in Scheme 13.



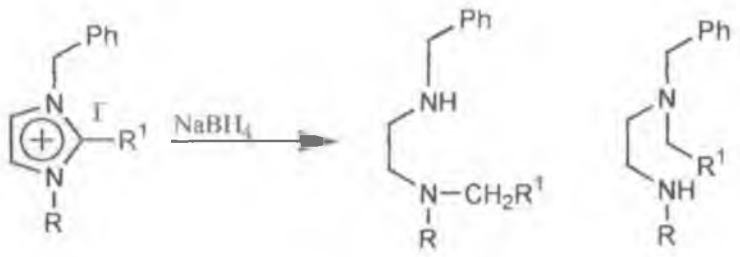
(27)

Scheme 13

1.3 Applications of 1,3-Disubstituted Imidazolium salts

1.3.1 Substituted Diamines

Treatment of imidazolium salts with excess sodium borohydride has been shown to lead to unsymmetrically substituted diamines.[20] Sodium borohydride cleaves the imidazolium ring predominately between C-2 and the substituted imidazole nitrogen N-1 or N-3 leading to the diamine products **(28)** and **(29)** as in Scheme 14.



(28) **(29)**

Scheme 14

The approach of the attacking hydride can be controlled by steric factors on N-1 or N-3, thus leading to a high degree of regioselectivity in the cleavage reaction as shown in Table 1.

Table 1.

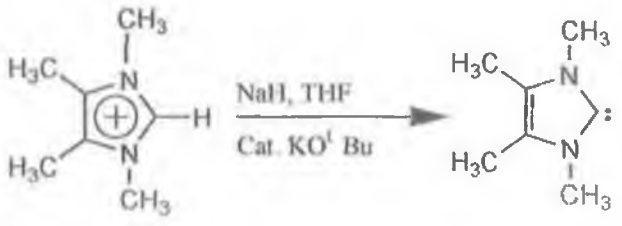
R	R^1	% Yield Product (28)	%Yield Product (29)
Me	H	85	8
Et	H	81	15
n-Pr	H	80	16
Me	Me	93	6
Et	Me	77	23

The above results would imply that at some stage of the reduction, attack of the hydride ion on C-2 occurs in a sterically controlled fashion away from the imidazolium nitrogen containing the sterically bulkier substituent.

1.3.2 Nucleophilic Carbenes

1.3.2.1 Synthesis of Nucleophilic Carbenes

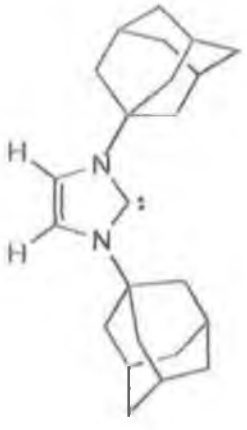
1,3-disubstituted imidazolium salts have proved to be useful precursors for the generation of heterocyclic carbenes *via* treatment of the imidazolium salt with a suitable base. The generation of the two carbene nonbonding electrons occurs at C-2 of the imidazole ring. An example of this reaction was reported by Arduengo *et al.*[21] The carbene **(31)** was obtained by treating 1,3,4,5-tetramethylimidazolium chloride **(30)** with 1 equiv. of sodium hydride in THF using 5 mol% potassium *tert*-butoxide as a catalyst (Scheme 15).

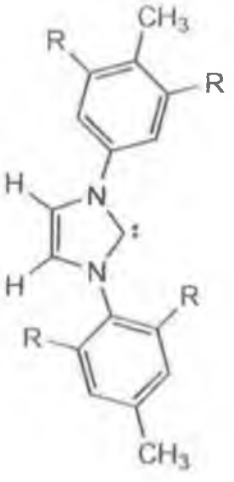


(30) **(31)**

Scheme 15

Other examples of nucleophilic carbenes prepared by this route are **(32)** and **(33)**, as shown below

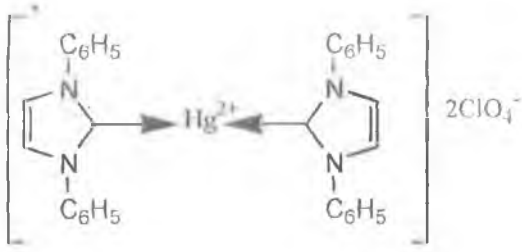




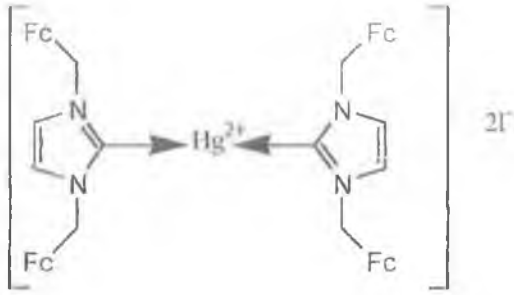
(32) **(33)**

These heterocyclic carbene compounds have nucleophilic properties and possess a significant degree of electronic stability which may be derived from a combination of steric and electronic factors. The electronic factors operate *via* both π and σ modes. In the π mode, electron donation into the carbene out-of-plane p-orbital by the electron rich system (N-C=C-N) leads to a moderation of the electrophilic reactivity of carbenes. In the σ mode, additional stability for the carbene electron pair may be gained from the σ electron-withdrawal effects on the carbene center by the more electronegative nitrogens. The overall combination of these σ and π effects, serves to increase the singlet-triplet gap and stabilise the singlet carbene over the more reactive triplet state. From a steric perspective, particularly in carbene **(32)**, the adamantyl substitutents could hinder the reaction of the carbene center with external reagents.

Nucleophilic carbenes derived from 1,3-imidazolium salt systems have been used in a variety of synthetic applications. They have been used in the direct synthesis of transition-metal carbene complexes[15, 22] examples of which are given below.



(34)



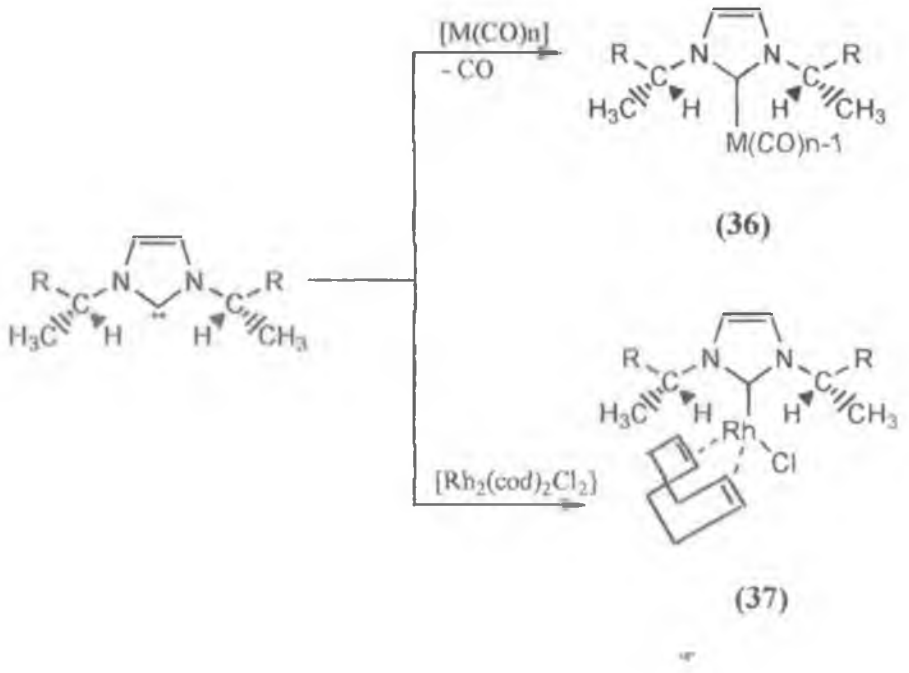
(35)

Fc = Ferrocene

1.3.2.2 Nucleophilic Carbenes as Asymmetric Catalyst Precursors

More recently, chiral heterocyclic carbenes derived from chiral 1,3-imidazolium salts have been investigated as controlling ligands in homogenous asymmetric catalysts.

Work carried out by Herrmann[23] yielded potential asymmetric catalysts such as **(36)** and **(37)** derived from reacting transition metal carbonyls or rhodium salts, with heterocyclic carbene ligands (Scheme 16).



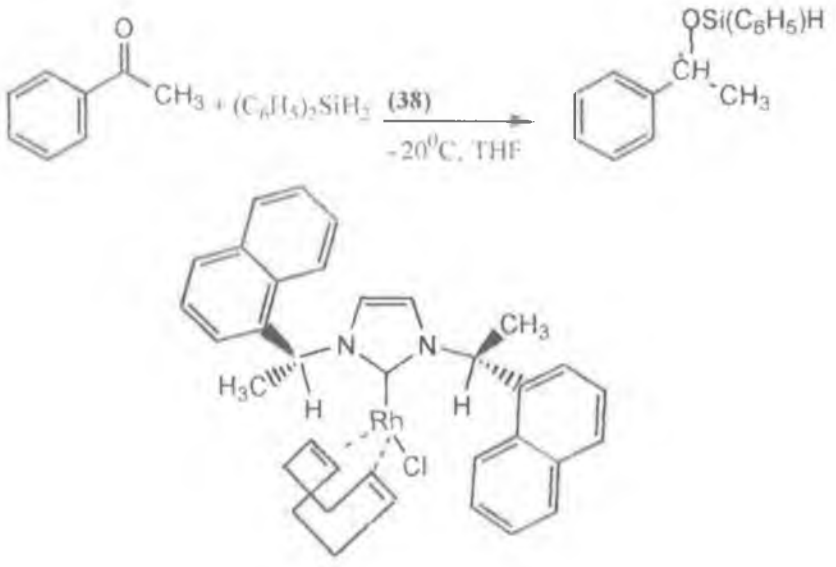
(36)

(37)

Scheme 16

It was found that these complexes possessed a high degree of thermal stability and air sensitivity, making them ideal candidates for use as asymmetric catalysts.

Catalyst **(38)** was used by Herrman in the study of the asymmetric hydrosilylation of acetophenone. The catalyst was found to allow almost quantitative conversion and optical inductions higher than 30% (Scheme 17).



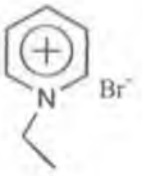
(38)

Scheme 17

1.3.3 Ionic Liquids

1.3.3.1 Organohaloaluminate Ionic Liquids

The term 'ionic liquid' is applied to a fused salt system that is liquid at room temperature. The discovery of the first ambient temperature organohaloaluminate ionic liquid was made by Hurley *et al.*[24] which was based on a combination of n-ethylpyridinium bromide **(39)** and aluminium chloride.



(39)

The discovery of organohaloaluminate salts and their ionic liquid properties have attracted much academic and industrial interest. The organohaloaluminate class of ionic liquids possess many unique properties in terms of solubility,[25] superacidity,[26] electrochemical,[27] and other physio-chemical aspects.[28] It has also been discovered that certain quaternised salts of imidazole, namely the 1,3-dialkylimidazolium salts, are also ideal molecules for the formation of organohaloaluminate ionic liquids.

An interesting facet of 1,3-dialkylimidazolium chloroaluminate ionic liquids is their adjustable Lewis acidity and, as they are liquids at room temperature, their utilisation both as catalyst and solvent in organic reactions.

The overall Lewis acidity or basicity of these organohaloaluminate systems depends greatly on the ratio of aluminium chloride to the quaternized salt as dictated by the following equilibrium, which will vary in different melts. Here, heptachloroaluminate anion, $Al_2Cl_7^-$, functions as a Lewis acid and the chloride anion, Cl^-, as a Lewis base (Scheme 18).

$$2AlCl_4^- \rightleftharpoons Al_2Cl_7^- + Cl^-$$

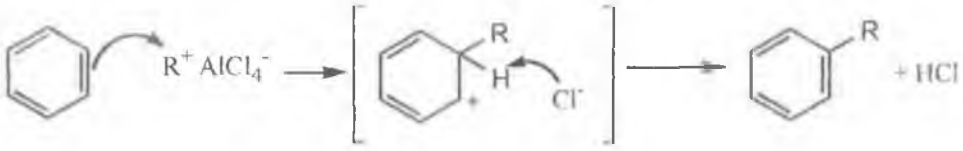
Scheme 18

In the initial discovery of 1,3-dialkylimidazolium chloroaluminate ionic liquids, Wilkes[29] reported that the equilibrium constant of 1-methyl 3-ethylimidazolium chloride melt **(40)** containing 44 mol% aluminium chloride was found to be of the order of 2.0 $x10^{-9}$, as determined by potentiometric methods.

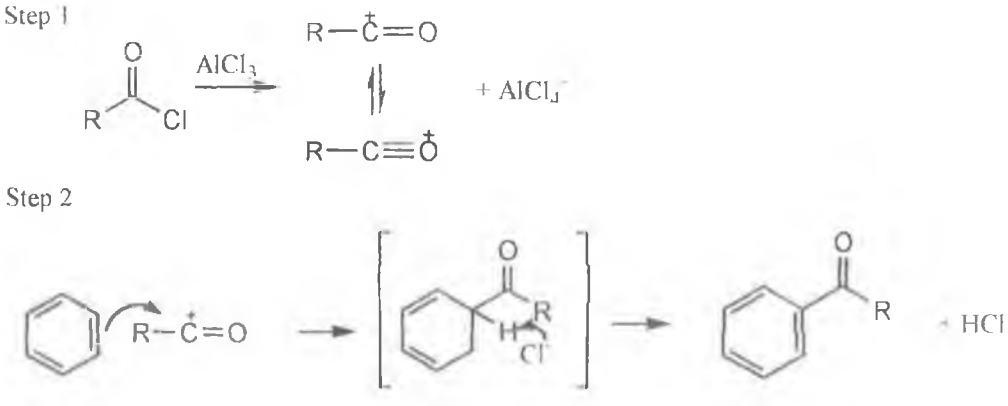
(40)

Wilkes also found that 1,3-dialkylimidazolium chloride/aluminium chloride melts were superior to previously discovered melts in terms of liquid state temperature range, electrochemical window, and reactivity with aluminium.

These discoveries created a considerable amount of interest in the utilisation of ionic liquids in organic reactions such as the Friedel-Crafts reaction.[30] Friedel Crafts electrophilic alkylation and acylation reactions on aromatic compounds are normally performed in an inert solvent at high temperature, and are catalysed by suspended or dissolved aluminium chloride as shown below in Schemes 19 and 20 respectively.



Scheme 19



Scheme 20

In studying Friedel-Crafts alkylation and acylation reactions on aromatic substrates Boon *et al.*[31] noted that basic melts of 1-methyl-3-ethyl imidazolium chloride and aluminium chloride exhibited no catalytic activity but acidic melts were extremely reactive. Since an acidic species is required to catalyse these reactions, compositions of a melt of **(40)** and aluminium trichloride were used. Hence the equilibrium as shown in Scheme 18, is influenced to favour the predominance of $Al_2Cl_7^-$.

This observation is consistent with the fact that pure $AlCl_3$ is not an effective catalyst in Friedel Crafts reactions, that traces of co-catalyst are necessary, and that a twofold excess of $AlCl_3$ promotes greater yields.[32] It is noteworthy that some of the alkylations carried out by Boone were done at temperatures of -25^0C with the melt still liquid.

Boone found that carrying out the Friedel-Crafts acylation of benzene using acetyl chloride **(41)** in 1-methyl-3-ethylimidazolium chloride **(40)** melts, readily occurs with mole fractions of aluminium chloride greater than 0.5M. ^1H NMR studies were carried out on the acetyl chloride/melt mixture to observe any possible interactions in the formation of acetophenone **(42)** (Scheme 21).

(41) **(42)**

Scheme 21

Observations on the shift of the methyl group in the ^1H NMR of acetyl chloride, or its product acetophenone, showed that the methyl shift depended very much on the relative concentrations of acetyl chloride and $Al_2Cl_7^-$ in the mixture. This observation was very suggestive of a stoichiometric reaction between acetyl chloride and $Al_2Cl_7^-$ which leads to the generation of the electrophilic acylium ion, CH_3CO^+ (Scheme 22).

$$CH_3COCl + Al_2Cl_7^- \longrightarrow CH_3CO^+ + 2AlCl_4^-$$

Scheme 22

Alternatively an undissociated reactive complex of $CH_3COCl\bullet\bullet\bullet\bullet Al_2Cl_7^-$ may be formed. In summing up the role of the ionic liquid as solvent and catalyst, Boone proposed the following mechanism given in Scheme 23.

$$RCO\text{-}Cl + Al_2Cl_7^- \rightleftharpoons RCO^+ + 2AlCl_4^-$$

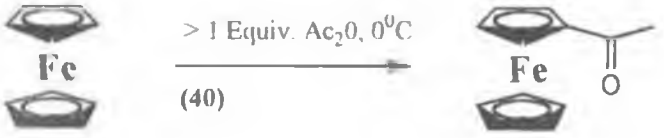
$$RCO^+ + Ar\text{-}H \rightleftharpoons H\text{-}Ar^+\text{-}CO\text{-}R$$

$$H\text{-}Ar^+\text{-}CO\text{-}R + AlCl_4^- \rightleftharpoons Ar\text{-}CO\text{-}R + HCl + AlCl_3$$

Scheme 23

The cationic intermediate H-Ar^+-COR may not be completely ionised acylium, but instead, the reaction may produce other species of equivalent stochiometry and reactivity.

The use of 1-ethyl 3-methylimidazolium halogenoaluminate **(40)** melts in Friedel-Crafts acylation have also been successful in the monoacetylation of ferrocene[53] using acetic anhydride. Yields of monoacetylated ferrocene **(43)** have been reported up to 90%, with reaction times of two hours and reaction temperature at 0 °C (Table 2). These findings were significant in highlighting the advantages of using dialkylimidazolium salts when performing reactions that involve thermally labile organometallic reactants and their intermediates (Scheme 24).



(43)

Scheme 24

Table 2

Mole ratio Ac_2O : Ferrocene	Reaction time (Hours)	Yield % Acetylated Ferrocene **(43)**
3:1	2	72
2:1	2	62
	4	84
1:1	2	31
	4	71

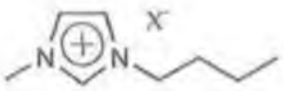
Organohaloaluminate ionic liquids have also been utilised as catalysts for oligomerization/polymerization of olefins and also for the alkylation of parrafins, iso-parrafins, and aromatic compounds with olefins.[54]

However, it is interesting to note that ionic liquids based on haloaluminate systems suffer from a sensitivity to water, which can make them difficult to handle as conventional reagents.

1.3.3.2 Other Ionic liquids based on 1,3- Imidazolium salts

The solubility properties of 1,3-dialkylimidazolium based ionic liquids are also of considerable interest in that they have been found to be immiscible with solvents of low polarity *eg.* ethers, haloalkanes, thus yielding possibilities for synthetic applications, particularly in bi-phasic catalytic systems.

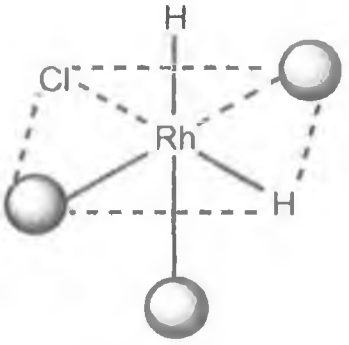
Suarez *et al.*[55] have demonstrated that the reaction of 1-butyl 3-methylimidazolium chloride **(44)** by the anion exchange with sodium tetrafluoroborate or sodium hexafluorophosphate in acetone produced room temperature, air and water stable ionic liquids.



$X = BF_4^-, PF_6^-$

(44)

These liquids were used in a two phase catalytic hydrogenation study between cyclohexene and octohedral rhodium complexes such as Wilkinsons catalyst **(45)**, $RhClH_2(PPh_3)_3$.[46]



 $= P(C_6H_5)_3$

(45)

It was found that solvation interactions between the catalyst **(45)** and **(44)** produced a stable solution from which the co-ordinated transition metal complexes could not be removed by non-polar solvents. This discovery was of special interest in that by their very nature rhodium complexes are quite soluble in non-polar solvents, are difficult to recover for the reaction mixture once hydrogenation of the substrate has been achieved in non-polar reaction media. A simplified version of the catalytic cycle is shown in Figure 1.

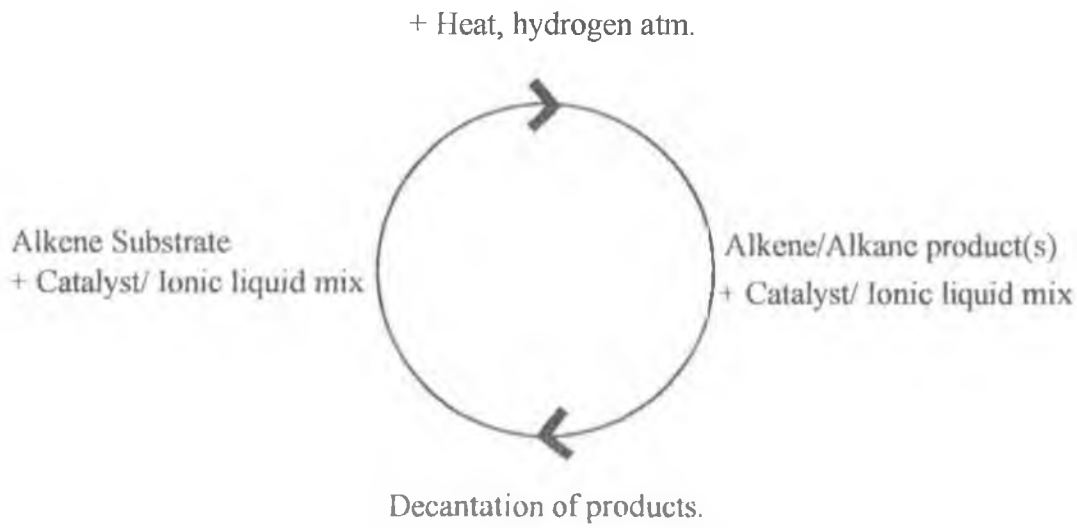


Figure 1

Test reactions involving the hydrogenation of cyclohexene was, using **(44)** as a solvent for the Wilkinson catalyst **(45)** was successfully carried out resulting in a percentage cyclohexane conversion in the range of 40-65% at room temperature.

It is important to note that at the end of each hydrogenation run, the product was removed from the two phase catalytic system by decantation, with the rhodium catalysts being contained in the ionic liquid. Also it was found that subsequent atomic absorption studies of the rhodium content of both phases after catalytic reaction indicated that more than 98% of metal is retained in the ionic phase. The use of ionic liquids in bi-phasic catalytic systems therefore created a facile route by which organometallic transition metal catalysts can be separated from reactant mixtures and easily re-used.

Other reactions of this type investigated include catalytic dimerizations using nickel-phosphine complexes,[37] olefin metathesis and butadiene dimerization,[28] and the hydrogenation, isomerization and hydroformylation of alkenes.[38]

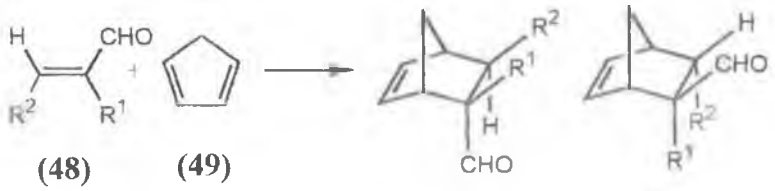
Recently, Howarth *et al.*[39] have investigated the use of 1,3-dialkylimidazolium salts **(46)** and **(47)**, as potential Lewis acids in the Diels-Alder reaction between

crotonaldehyde/methacrolein and cyclopentadiene. However, in this case it is the cationic imidazolium centre itself, which was investigated as a potential Lewis acid.

(46a) X= Br^-
(46b) X= CF_3COO^-

(47)

The above imidazolium salts (0.2mol. equivalents) were stirred in dichloromethane for 48 hours with the dienophile **(48)** and cyclopentadiene **(49)** at 25^0C under nitrogen (Scheme 25). The adduct endo:exo ratios were determined by ^{1}H NMR *via* the integration ratios of the adduct aldehydic protons. The endo:exo ratios and the percentage adduct yields are shown in Table 3.



(48) **(49)**

Endo Exo

Crotonaldehyde: $R^1 = H$, $R^2 = Me$
Methacrolein: $R^1 = Me$, $R^2 = H$

Scheme 25

Table 3.

Dialkylimidazolium salt	Crotonaldehyde reaction		Methacrolein reaction	
	% Yield	Endo: Exo	% Yield	Endo exo
46 a)	35	95 : 5	40	15 : 85
46 b)	37	95 : 5	40	13 : 87
47	36	93 : 7	36	10 : 90

The above endo:exo ratios demonstrated that the tested dialkylimidazolium salts had potential as Lewis acid catalysts. However, the yields of the adduct showed that they acted as weak Lewis acids. The chiral imidazolium salt (47) offered an opportunity to test the imidazolium cation centre as a possible Lewis acid catalyst for asymmetric catalysis. Howarth reported an enantiomeric excess < 5% using the above experimental conditions. However, the development of Lewis acid catalysts, and indeed possible asymmetric Lewis acid catalysts based on the 1,3-disubstituted imidazolium cation centre demonstrated much potential.

Quaternized imidazolium salts have also been used in other applications such as pharmaceuticals in the treatment of toxic poisoning by organophosphorous compounds,[13] and exploiting the cationic imidazolium center to form potential conducting polymers.[10]

1.4 Ferrocene

Ferrocene **(50)** was first reported by Kealy and Pauson in 1951[41] as a product from the reaction of cyclopentadienyl magnesium bromide in benzene with anhydrous iron(III) chloride in diethyl ether.

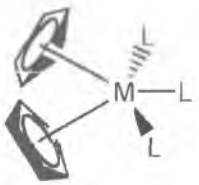
(50)

Ferrocene is described a 'sandwich compound' *ie.* an iron atom sandwiched between two cyclopentadiene rings. Its essential feature is the symmetrical binding of the central metal atom to all five carbon atoms of each ring. Only a single covalent bond links the metal to each ring so that the structure cannot properly be described in classical valency-bond terms. A *d*-orbital of the metal must be available for such bonding, a condition satisfied by the transition metals, all of which have been shown to yield such cyclopentadiene derivatives. Examples of other sandwich compounds include nickelocene, cobaltocene, chromocene, and ruthenocene to name but a few.[42]

It was quickly recognised that the cyclopentadiene rings of ferrocene are free rotating and that the barrier to this internal rotation was quite low as determined by electron diffraction and low temperature crystal studies.[43]

Ferrocene belongs to a class of organometallic compounds known as the η5-cyclopentadienyl complexes which can be classified as symmetric molecules with parallel cyclopentadiene rings **(51)**. They can form 'bent metallocenes' in which the two cyclopentadienyl rings are not parallel and having from one to three additional ligands L **(52)**, and 'half-sandwich' compounds in which L represents one to three ligands **(53)**.

(51)



(52)

(53)

The cyclopentadienyl moiety of ferrocene possesses considerable aromatic character, which was first demonstrated by Woodward, Rosenblum, and Whiting in 1952[44] where it has been shown that ferrocene does not undergo addition reactions with maleic anhydride or hydrogenation reactions in the presence of Adam's platinum oxide catalyst. As benzene rings are attacked under these conditions, the ferrocene molecule may be much more aromatic in character than benzene. These observations were further confirmed in that ferrocene readily undergoes Friedel-Crafts acylation under mild, stoichiometrically controlled conditions to give exclusively mono or di-substituted products.[45]

Ferrocene is also readily oxidised to the ferrocenium cation **(54)** by electron transfer reactions. The action of various inorganic and organic oxidising agents such as nitric acid, iron (III) chloride, quinone, and N-bromosuccinimide on ferrocene will promote a one-electron oxidation of the iron atom to the ferrocene cation (Scheme 26)

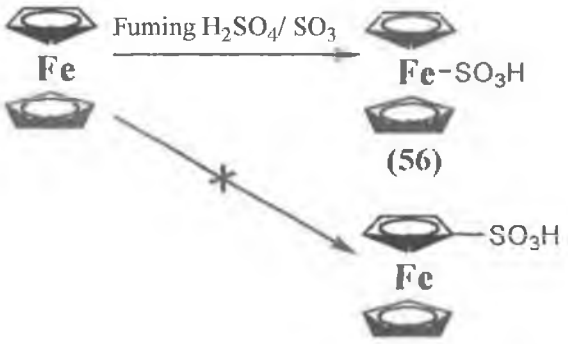
(54)

Scheme 26

This tendency to undergo a one-electron oxidation can cause synthetic problems from an electrophilic substitution viewpoint. Ferrocene will also readily undergo protonation in strong acidic media on the metal atom which can also pose synthetic problems. Rosenblum and co-workers found that protonation of ferrocene led to the formation of the structure **(55)**.[46]

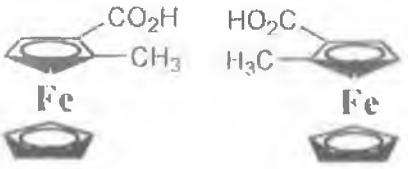
(55)

This observation further confirmed the decreased susceptibility of ferrocene to electrophilic substitution reactions that would otherwise apply to other aromatic compounds. It was concluded that electron density of the cyclopentadienyl rings is drawn towards the oxidised iron atom thus inactivating them to electrophilic attack.
For example, unlike benzene, sulphonation of ferrocene cannot be carried out using conc. sulphuric acid because of oxidation to the ferrocenium cation to yield **(56)** (Scheme 27).



Scheme 27

An interesting aspect of substituted ferrocene derivatives is their potential to form chiral compounds, which can possess chirality that is both central and planar. For example the illustrated ferrocene derivatives **(57)** and **(58)**, possess a plane of chirality through the metal centre and thus their two forms are non-superimposable. Each isomer will rotate plane polarised light in opposite directions.



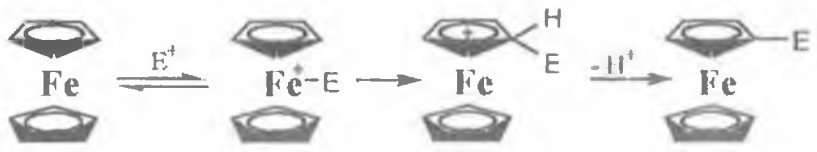
S- **(57)** R- **(58)**

1.5 Synthesis of Substituted Ferrocenes

1.5.1 Electrophilic Substitution

Of the metallocenes, those of iron, ruthenium and osmium are exceptional in undergoing facile electrophilic substitution reactions, most others being oxidatively destroyed by common electrophiles. However, as discussed previously, even these metallocenes can oxidise to the ions with the general formula $[M(C_5H_5)_2]^+$.

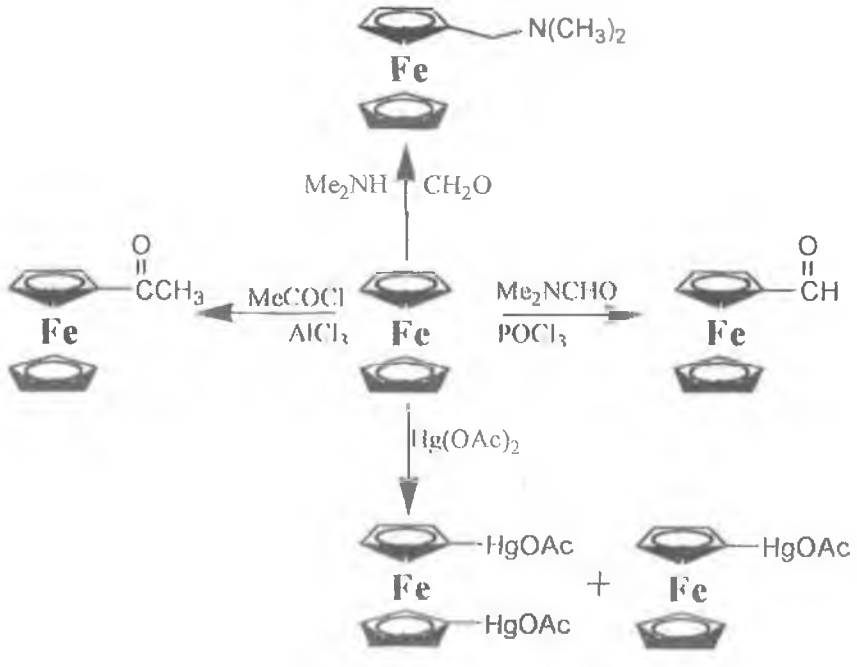
The mechanism of electrophilic substitution of ferrocene involves an initial step involving the electrophile and the *d*-orbital electrons of the iron atom to yield a charge transfer complex **(59)**, which effectively then transfers to the cyclopentadienyl ring to effect the completed substitution with the subsequent loss of a proton (Scheme 28).



(59)

Scheme 28

Scheme 29 features some well known examples of electrophilic substitution of ferrocene.



Scheme 29

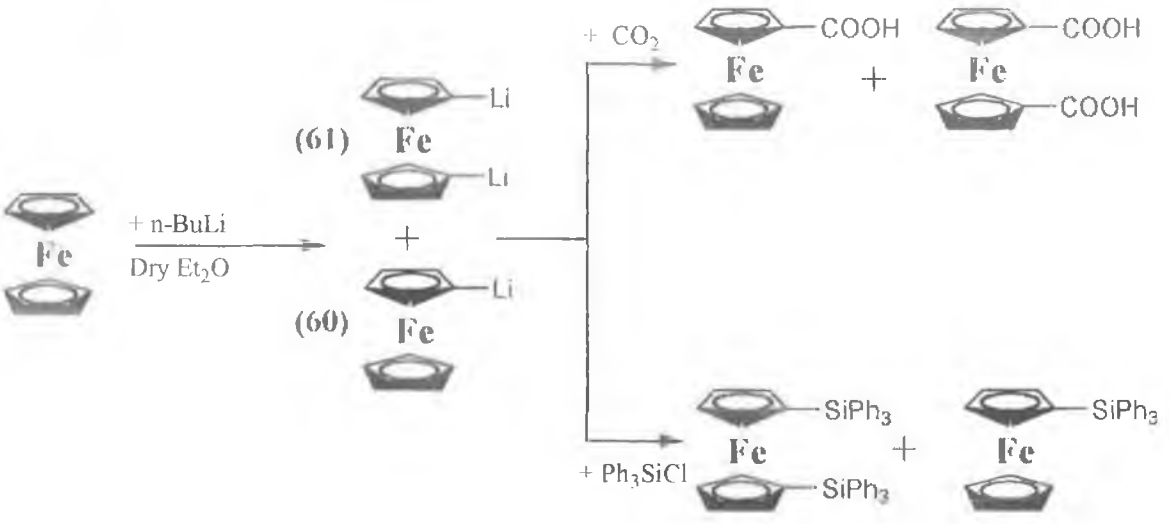
1.5.2 Metallation Reactions

The reaction of an organic compound containing a relatively acidic hydrogen atom (R-H) and an organolithium reagent (R_1-Li) is usually referred to as the hydrogen-lithium interchange or metallation reaction (Scheme 30).[47]

$$R{-}H + R^1{-}Li \xrightarrow{Solvent} R{-}Li + R^1{-}H$$

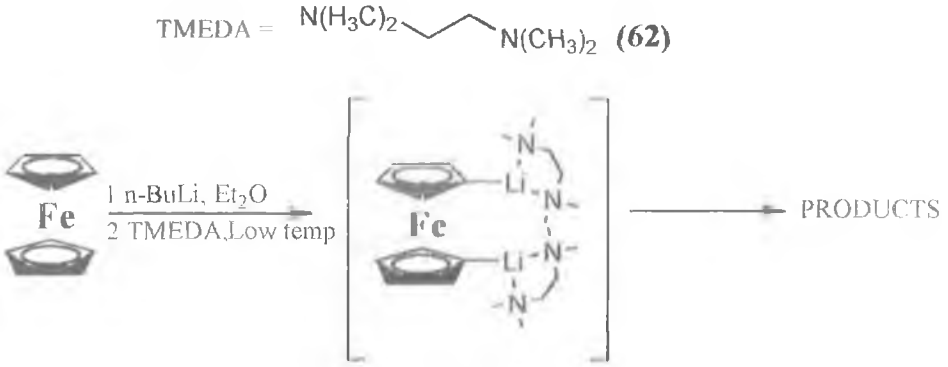
Scheme 30

Ferrocene readily undergoes metallation, particularly with organolithium compounds, the lithiated derivatives being very useful precursors in the synthesis of many substituted ferrocenes. This discovery, initially noted by Benkeser,[48] further reinforced the comparative reactivities of ferrocene and benzene in that benzene itself does not appreciably react with these reagents, indicating that the hydrogen atoms in ferrocene are much more acidic. Benkeser found that the lithiated ferrocene intermediates **(60)** and **(61)** gave rise to mixtures of mono and 1,1' disubstituted ferrocenes as shown in Scheme 31.



Scheme 31

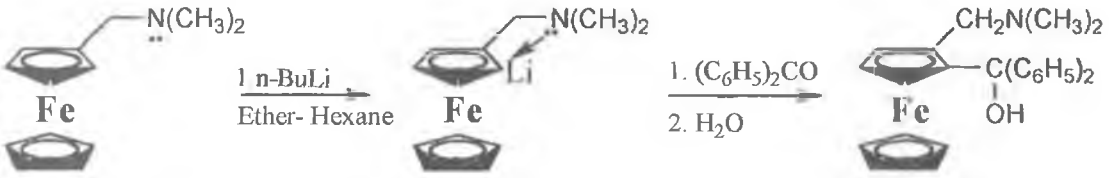
The lithiated salt of ferrocene may be prepared by treating ferrocene with stochiometric quantities of an alkyl lithium compound, for example, *n*-butyl lithium in hexane-ether mixtures. The lithiation reaction for ferrocene is very much dependant on the reaction stoichiometry between the organolithium reagent and ferrocene. The control of reaction temperature, and type of solvent used are critical in that undesirable polylithiated side products may occur. Rebiere and co-workers reported a convenient method for synthesising predominately mono-lithiated ferrocene[49] by using *t*-butyl lithium in THF, with yields of monolithiated ferrocene of up to 70%. A method where 1,1'- di-lithiated ferrocene may be prepared free from the mono-lithium derivative by using n-butyl lithium in the presence of TMEDA (N,N,N',N',-tetramethylenediamine) **(62)** was discovered by Rausch and Capinelli in 1967[48] which gave rise to exclusively 1,1'-disubstituted ferrocene compounds in high yields. The use of TMEDA greatly enhances the basicity of the organolithium reagent in its ability to chelate the lithium cation **(63)**, leaving a greater negative charge on the carbo-anionic site (Scheme 32).



(63)

Scheme 32

Regioselectivity in the lithiation of ferrocene derivatives may be possible in an *ortho* fashion *via* a five membered chelate ring transition state, provided that the initial ferrocene derivative contains groups that have electron lone pairs. This phenomenon was first noticed by Jones and co-workers in the ortho lithiation of benzyldiethylamine[51] and was later employed by Slocum *et al.*[52] in the preparation of the 1,2-disubstituted ferrocene **(66)** from the condensation of n,n–dimethylaminoferrocene **(64)** and benzophenone (Scheme 33).

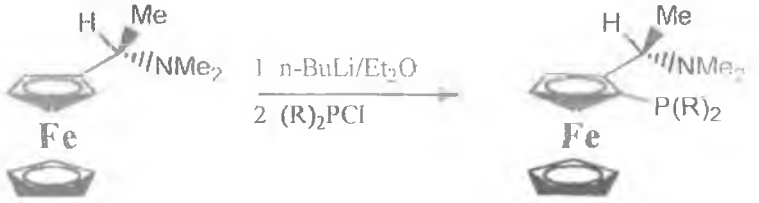


(64) **(65)** **(66)**

Scheme 33

It is thought that the transition state presumably involves co-ordination of the lone pair electrons with lithium **(65)**.

Hayashi [53] used this lithiation procedure in the formation of chiral diphenylphosphine derivatives of ferrocene, from enantiomerically pure ferrocenylethyldimethylamine **(67)**[54] which possessed both central and planar chirality aspects as shown in Scheme 34.



S/R- (67)

(S) - (R) - PPFA (R = Ph)

(R) - (S) - MPFA (R = Ph)

Scheme 34

1.5.3 Nucleophilic Substitution

Ferrocene will undergo nucleophilic displacement reactions *via* suitable derivatives such as haloferrocenes derived from lithiated ferrocene precusors.[55] These compounds are synthetically useful in preparing ferrocene derivatives which cannot be derived from more commonly utilised electrophilic substitution or metallation routes.

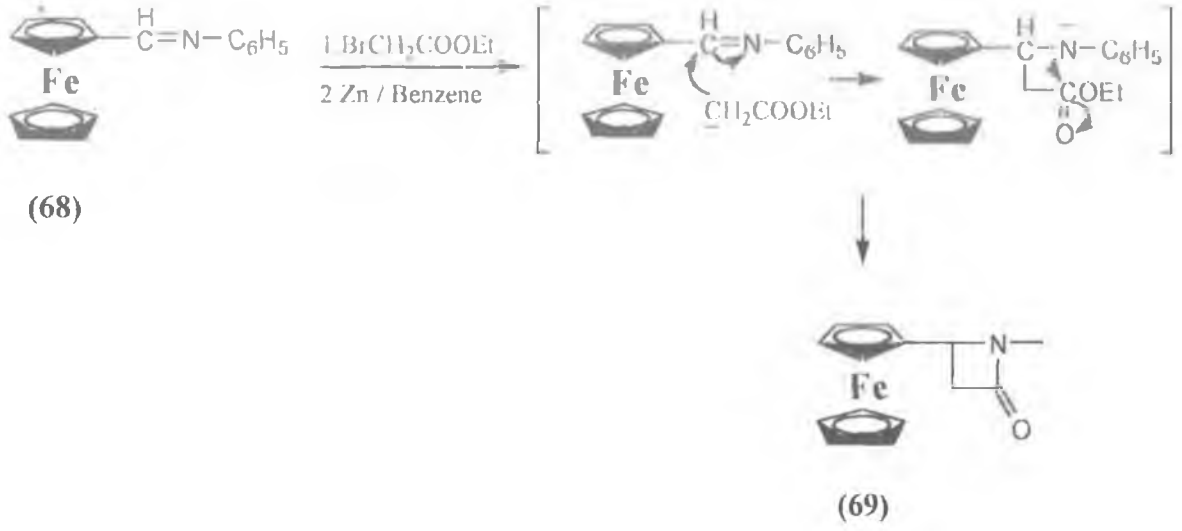
Examples of nucleophilic displacement reactions of ferrocene are given below in Scheme 35.

Scheme 35

1.6 Synthesis of Ferrocene Heterocycles

1.6.1 Azetidinones

Among the first ferrocenyl heterocyclic compounds with nitrogen containing rings have been azetidinone based **(69)**. These compounds were prepared by a Reformatsky reaction of the ferrocenyl aldimine **(68)**, with zinc and ethyl bromoacetate (Scheme 36).[56]



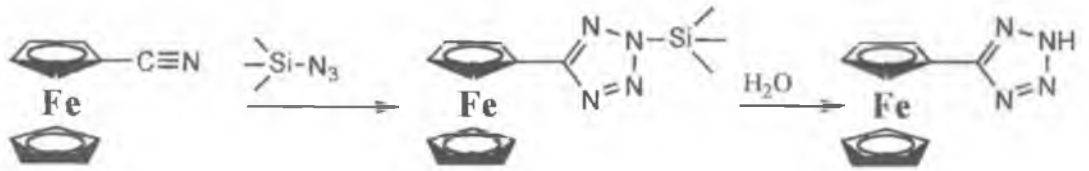
(68)

(69)

Scheme 36

1.6.2 Ferrocenyl Tetrazoles

Ferrocenyltetrazole **(71)** was successfully prepared by Washburne and Peterson[57] *via* the 1,3-dipolar cyclisation of trimethylsilyl azide and cyanoferrocene **(70)** together in the presence of aluminium trichloride as in Scheme 37.

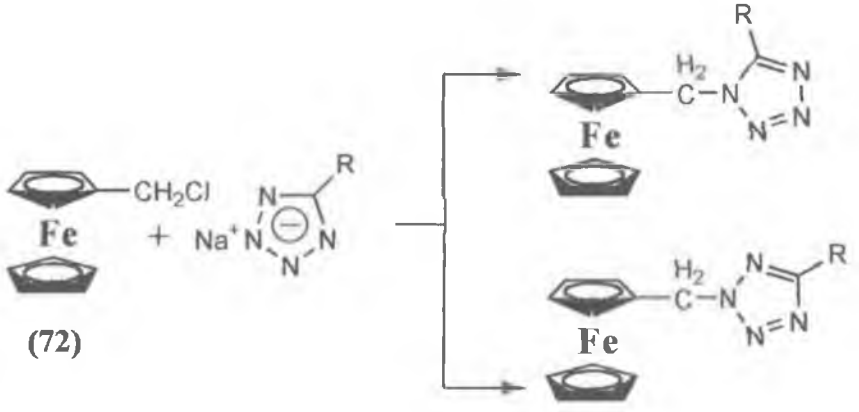


(70) **(71)**

Scheme 37

It is interesting to note that the use of aluminium chloride in the reaction is thought to polarise the nitrile group of the cyanoferrocene to form the intermediate species Fc-C…N-$AlCl_3$ which undergoes nucleophilic attack by the azide 1,3-dipole to exclusively yield compound **(71)**.

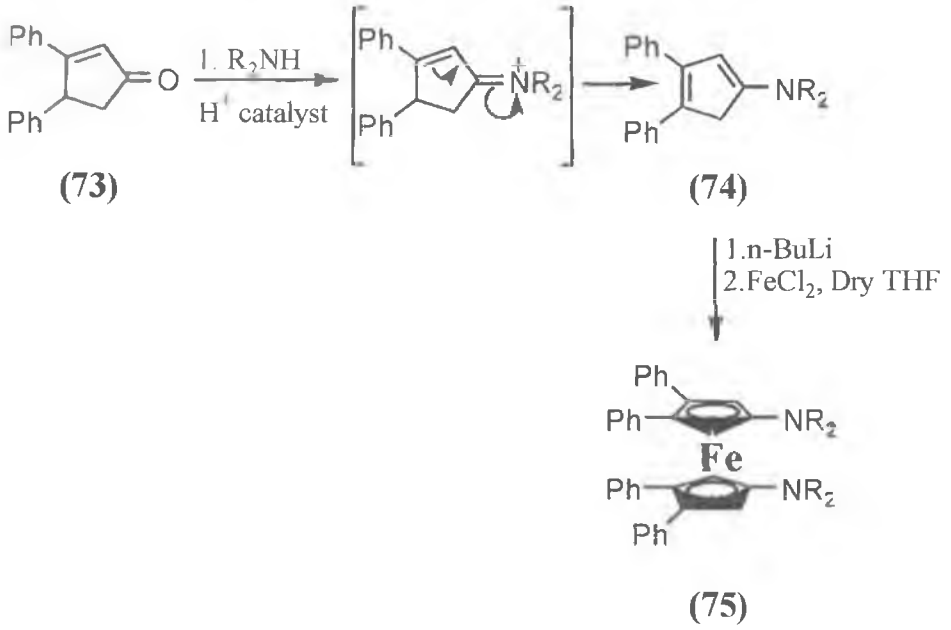
Another convenient route to ferrocenyltetrazoles is by reaction between the sodium salts of tetrazoles with chloromethyl ferrocene **(73)** as illustrated by the following example (Scheme 38).[58]



Scheme 38

1.6.3 Use of Enamine Intermediates

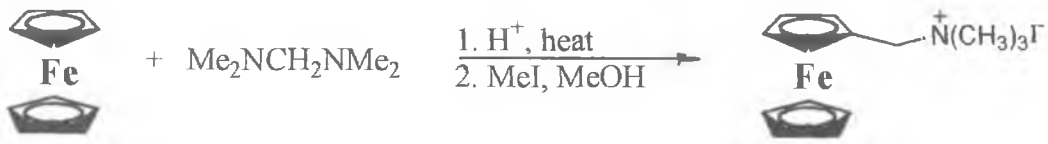
Plenio and Burth[59] utilised a synthetic route to making of novel aminoferrocene compounds. Unlike the above modes of synthesis, the ferrocene derivative was created indirectly by first preparing an alkylaminocyclopentadiene **(74)** *via* enamine formation of 3,4-diphenylcyclopent-2-enone **(73)** with various secondary amines.
The enamine derivatives are subsequently de-protonated with n-butyl lithium to form the stable mono-lithiated salts. Subsequent treatment of the lithium salts in a 2:1 molar ratio with ferrous chloride formed the ferrocene moiety **(75)** (Scheme 39).



Scheme 39

1.6.4 Ferrocenyl Imidazolium Compounds

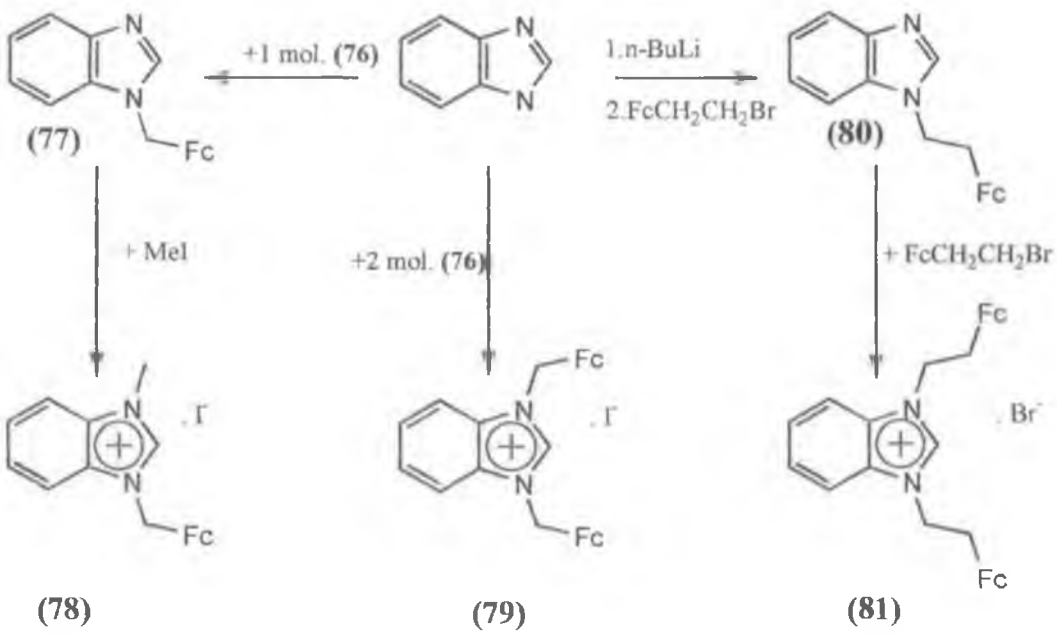
Recently, Bildstein[22] reported the formation of ferrocenyl salts containing quaternized imidazole and benzimidazole moieties. The reactions were carried out by two distinct routes. The first route employed the use of the well known monosubstituted ferrocene compound, n,n- dimethylamino-methylferrocene methiodide salt **(76)**, which is easily prepared by the electrophilic substitution reaction between ferrocene and N,N,N',N'-tetramethylmethylenediamine and subsequent quaternisation with methyl iodide, as shown in Scheme 40.[60]



(76)

Scheme 40

As this derivative possesses the very good leaving group of trimethylamine, it has long been known to be an excellent electrophile. By refluxing **(76)** together with either benzimidazole or imidazole, the corresponding ferrocene heterocycles of **(77)** were prepared. Further reaction of these derivatives with another equivalent of **(76)** or indeed an alkyl halide, resulted in quaternized heterocyclic salts with one or two ferrocene units incorporated such as **(78)** and **(79)**. The other route involved the use of alkyl haloferrocene derivatives, in this case (2-bromoethyl)ferrocene, which was reacted with the mono-lithiated derivative of benzimidazole or imidazole to yield derivatives of **(80)** in a similar fashion (Scheme 41).



(78) **(79)** **(81)**

Fc = Ferrocenyl

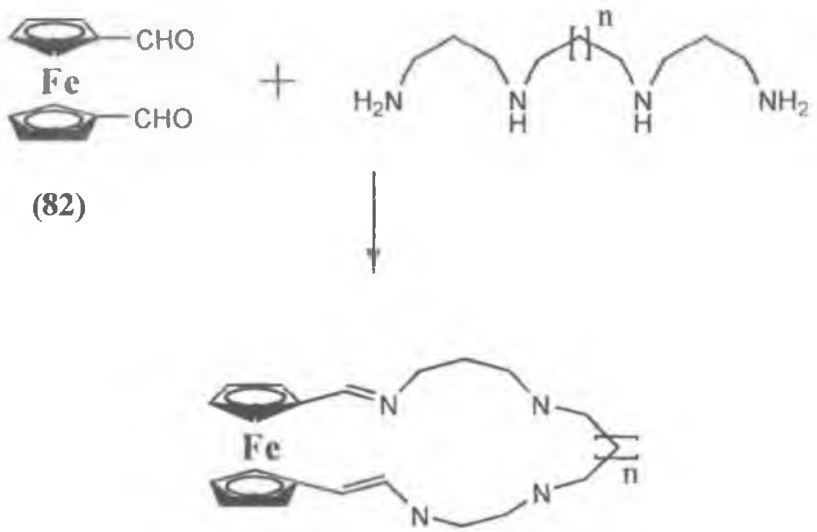
Scheme 41

Prolonged reflux of an additional mol. equivalent of alkylhaloferrocene resulted in the formation of the quaternized salt derivative **(81)**. Howarth's group also report high yield syntheses for quaternized ferrocenylimidazolium salts[61,62] using similar

synthetic strategies and these are discussed in more detail in chapter two and five of this thesis.

1.6.5 Bridged Ferrocene Heterocycles

Beer's group[63] used the readily available starting material ferrocene-1,1'-dicarbaldeyhde **(82)** which, when condensed with an appropriate diamine yielded a variety of heterocyclic bridged ferrocene structures **(83)** which are Schiff base products (Scheme 42).



(82)

(83)

n = C_2,C_3,C_4 etc.

Scheme 42

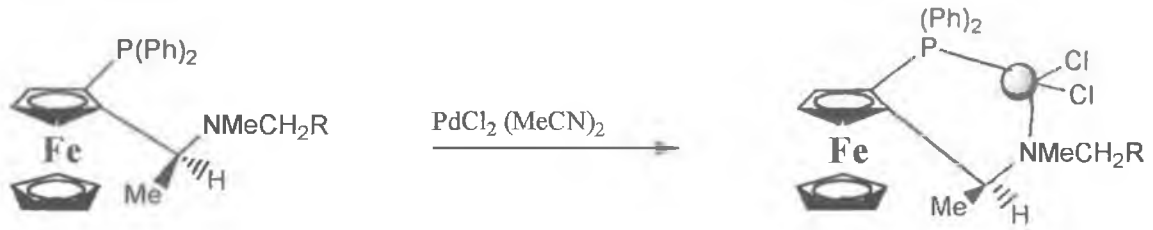
1.7 Applications of Substituted Ferrocene Derivatives

1.7.1 Asymmetric Catalysis

The chirality aspects of substituted ferrocenes, as discussed previously, open up the possibility of using chiral ferrocene derivatives, particularly ferrocenylphosphine

derivatives, in the design of asymmetric catalysts. Much research has been done in this area of ferrocene chemistry.

Hayashi and co-workers prepared a chiral catalyst[64] from an optically active ferrocenylmonophosphine derivative which contained a perflouroalkyl moiety **(84)**. The perfluoroalkyl side chain was found to enhance the solubility of the palladium complexes of this chiral ligand under reactant conditions (Scheme 43).



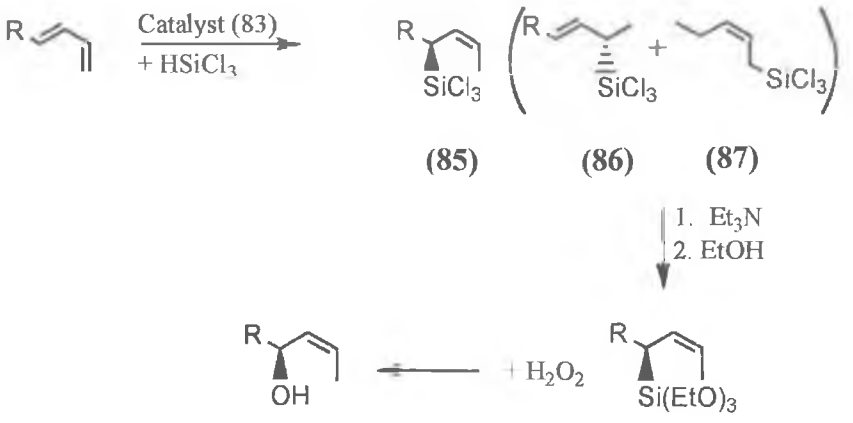
Catalyst **84a)** R = C_3F_7

Catalyst **84b)** R = C_8F_{17}

= Pd.

Scheme 43

The catalysts were examined for catalytic activity and stereoselectivity in the asymmetric hydrosilylation of conjugated dienes with trichlorosilane. The catalyst was found to produce predominately (Z)-2-butenylsilanes **(85)** and two other by-products **(86)** and **(87)**, with high regio- and stereoselectivity. The intermediate **(85)** was then converted into the corresponding optically active allyl alcohol **(89)** by oxidation of the carbon-silicon bond of the allyl(triethoxy) silane **(88)** (Scheme 44).



Scheme 44

The results for these catalyst systems are tabulated below in Table 4.

Table 4

(R)	Cat.	Rxn. Temp (°C)	Rxn. Time (hours)	% yield of **(85)**	Diastereoisomer ratio **(85/86/87)**
Cyclohexyl	**84 a)**	50	140	92	92:1:7
n-propyl	**84 a)**	50	60	97	92:2:7
Phenyl	**84 a)**	30	90	91	93:7:0
Phenyl	**84 b)**	80	20	64	81:19:0
Phenyl	**84 b)**	30	90	94	91:9:0

The above regio- and stereochemical results may be explained by the catalytic cycle where the key intermediate is a π-allylpalladium complex (Figure 2) substituted with *anti*-methyl and *syn*-alkyl groups, which are formed by the regioselective hydropalladation of the diene in a cisoid conformation.

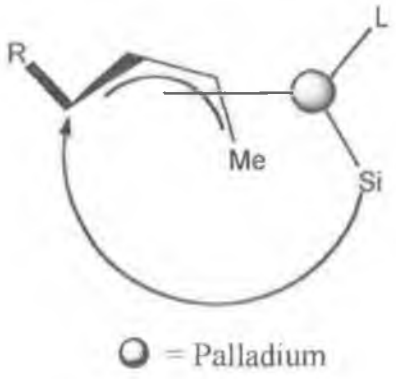
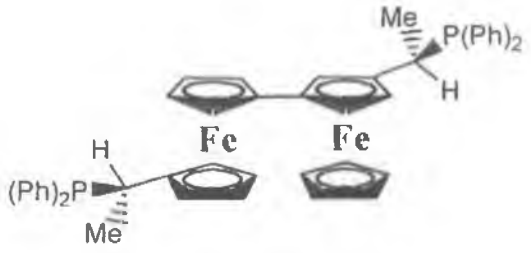


Figure 2

Chiral diphosphine ligands generally co-ordinate to transition metals in a predominately *cis* manner but further work carried out by Ito[65] has led to a bridged biferrocene ligand 2,2"-bis[1-(diphenylphosphino)ethyl]-1,1"- biferrocene **(90)** that possesses both central and planar chirality.



(90)

When this ligand is coupled to palladium(II) or platinum(II) salts the formation of asymmetric catalysts where the metal centre is co-ordinated in a *trans* manner to the ferrocene ligand (Figure 3) has been found to occur. This created possibilities for new asymmetric catalysts.

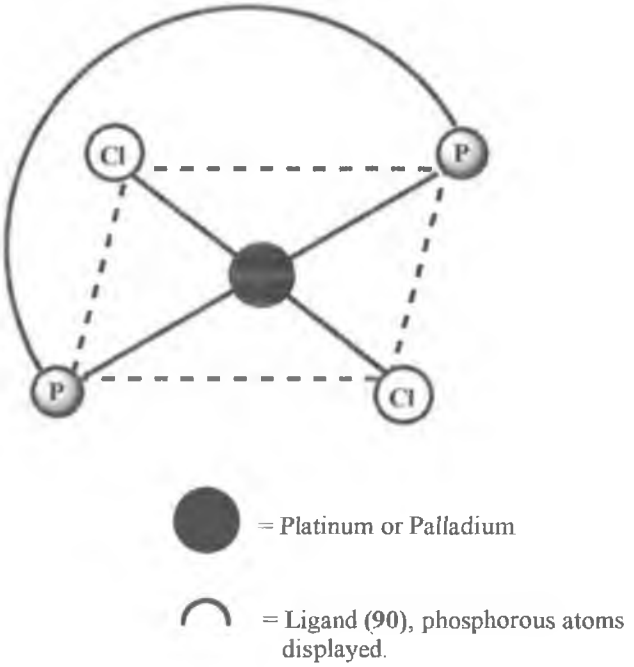
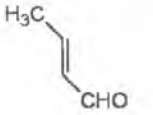
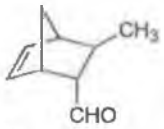
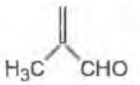
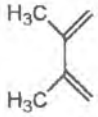
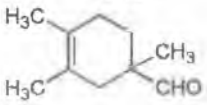
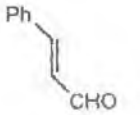
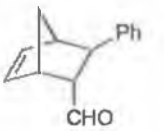
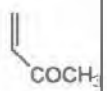
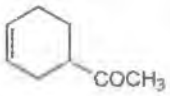


Figure 3

Kelly and co-workers have recently established that the hexafluorophosphate salt of the ferrocenium cation **(91)** acts as a potential Lewis acid catalyst in the Diels-Alder reaction[66] as shown in Table 5. These findings may point to the possibility that other metallocene derivatives may also exhibit useful Lewis acid behaviour. The potential is also there for the creation of new asymmetric Lewis acid catalysts based on the ferrocenium cation.

(91)

Table 5

Dienophile	Diene	Reaction conditions (temp. / time / equiv. of catalyst)	Yield %	Endo/ exo ratio	Product	Conditions for uncatalyzed rxn.
		0 ^{0}C/ 3h / 0.5	78	81/19		100^{0}C / 4h
		20 ^{0}C / 48h / 0.5	67	-		150 ^{0}C / 5h
		0 ^{0}C/ 20h / 0.2	59	88/12		No reaction at 20 ^{0}C
		20 ^{0}C / 36H / 0.5	80	-		140 ^{0}C / 8-10h

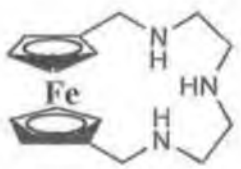
1.7.2 Co-ordinated Metal Receptors

Much interest has been generated in the development of receptor molecules that contain a redox centre in close proximity to a cation/anion binding site. These molecules can be designed to recognise electrochemically the binding of a charged guest either *via* interactions through space or *via* various bond linkages between the receptor site and the redox centre. In the case of a typical ferrocene receptor molecule, the ferrocene moiety acts as the redox-active centre, and the presence of

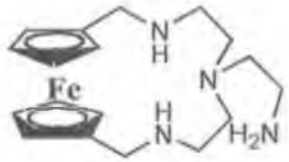
binding sites such as lone pair electrons present in nitrogen containing moieties, can form potential receptor molecules.

In electrochemical terms, the overall cathodic or anodic shifts of these ferrocene derivatives can be considerably altered depending on the electrochemical nature of the guest that is effectively 'co-ordinated' to the binding site of that derivative.

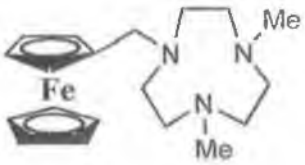
Beer[63] and co-workers first recognised the use of bridged ferrocene derivatives which electrochemically recognise Ni^{2+}, Cu^{2+}, and Zn^{2+} metal cations in aqueous environments. Beer used easily prepared polyaza and polyammonium ferrocene macrocycles **(92) (93)** and **(94)**, which have nitrogen lone pairs, capable of binding transition metal cations.



(92)



(93)



(94)

Transition metal co-ordination investigations with $Ni(ClO_4)_2$, $Cu(BF_4)_2$ and $Zn(ClO_4)_2$ led to the conclusion that a 1:1 ligand to metal stoichiometry occurred in these ferrocene ligands, and this was confirmed by elemental analysis.

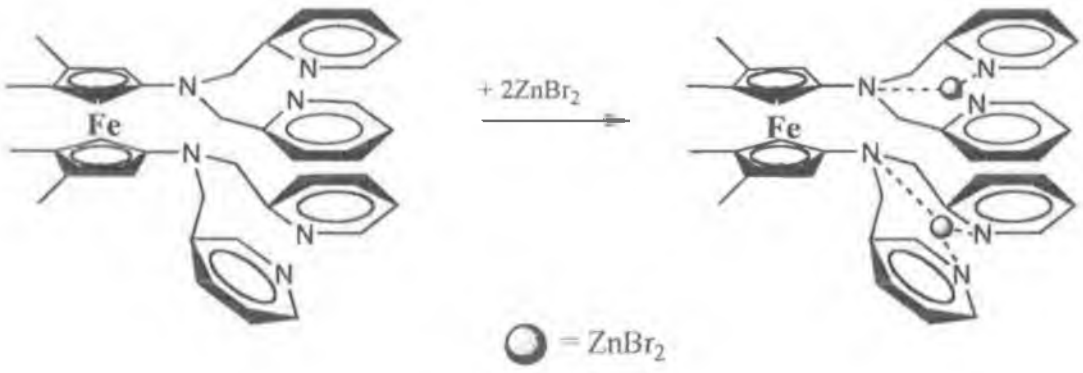
Electrochemical data for the various ligands on their own and with complexed metal ions showed significant shifts in the anodic current peak potential of the ferrocene/ferrocenium couple, $E_{1/2}$, for each ligand. These results further reinforce the idea that these molcules had the ability to 'recognise' different metal cations as shown in Table 6.

Table 6

Compound	**92**	**93**	**94**
$E_{1/2}$ (free) mV	215	210	235
$\Delta E_{1/2} Cu^{2+}$ mV	25	30	40
$\Delta E_{1/2} Zn^{2+}$ mV	105	40	30
$\Delta E_{1/2} Ni^{2+}$ mV	60	< 10	< 10

In 1996 however, Plenio and Burth[67] noted that in the case of substituted ferrocene derivatives containing these donor ligands, the metallocene to ligand linkage is separated by a methylene group, which can electronically insulate the redox centre of ferrocene from the ligand/guest ion complex. A process was proposed in which a transmission of electronic effects *via* bonding electrons as opposed to Coulomb effects through space would be more efficient. The best way to realise this would be to directly link at least one donor atom of a chelating moiety to the cyclopentadienyl ring of ferrocene.

An example of what Burth and his co-workers were trying to achieve is illustrated in Scheme 45 by the interaction between ferrocene ligand **(95)** and zinc(II) bromide.



(95)

Scheme 45

Electrochemical studies of the ferrocene ligand **(95)** with addition of a one molar equivalent of zinc salt , followed by a second mol equivalent, revealed that the change in half-wave potential of cyclic voltammograms dramatically doubled. This observation gave a strong indication that the zinc metal co-ordinated directly to the nitrogen atoms attached to the ferrocene centre. Indeed, this observation reinforced the hypothesis that the nitrogen atom linked to the cyclopentadienyl ring of ferrocene acted as a highly efficient mediator of electronic communication, as shown in Table 7.

Table 7

Cation added (mol. Equiv.)	E½ (V) (no cation added)	E½ (V) (Metal salt)	ΔE½ (mV)
1 Zn^{2+}	- 0.10	+ 0.23	+330
2 Zn^{2+}		+ 0.62	+720
3 Co^{2+}	- 0.10	+ 0.28	+380
4 Co^{2+}		+ 0.66	+760

The x-ray crystal structure of the zinc complex of ligand **(94)** shows how the two $ZnBr_2$ units are easily accomodated since the two metal ions and the dipicolylamino unit are located above and below the ferrocene unit (Figure 4).

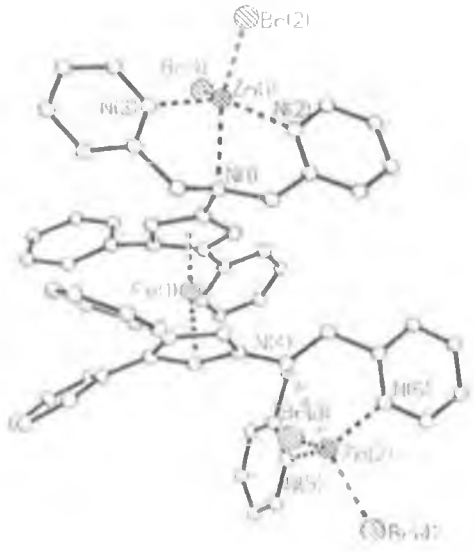


Figure 4

It is indeed evident that ferrocene based compounds offer a diverse range of possibilities in the various disciplines contained within the science of chemistry as a whole. Initially this work will look at the synthesis of these compounds that contain an imidazolium centre, with a view to designing efficient Lewis acid catalyst systems. However, in view of the recent developments made in receptor molecule design, the anionic receptor properties of these new compounds will also be investigated.

CHAPTER 2

PREPARATION OF THE FERROCENYLIMIDAZOLIUM SALTS

2.1 Introduction

The initial aim of this work was to explore the potential of the cationic imidazolium center in the creation of novel Lewis acid catalysts, based on the initial findings of Howarth.[39] The incorporation of ferrocene into the imidazolium moiety could also serve to improve on previous reported imidazolium salts and their applications, from a number of perspectives as described below.

a) The ferrocene moiety can be easily converted to the ferrocenium cation[66] which could yield a receptor molecule with two potential binding sites for anions This could possibly lead to bi-dentate co-ordination of anionic guest species, *via* the ferrocenium center and the imidazolium center as shown in Figure 5. Indeed, the possibility of constructing Lewis acid catalysts with two possible catalytic centres could also be realised in this way.

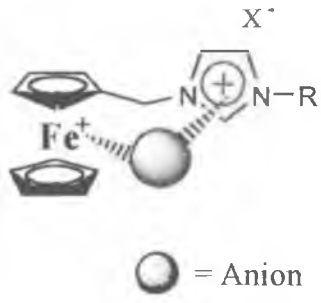
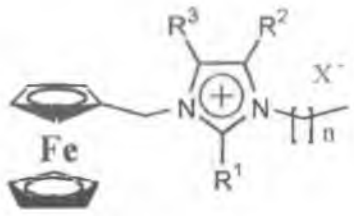


Figure 5

b) Treatment of the ferrocenylmethylimidazolium salt with an appropriate base could generate the corresponding carbene, which could subsequently be used to create stable metal-carbene complexes[22,23] such as those shown in Scheme 16. With the option of using chiral ferrocenes in the catalyst design, the possibility of new asymmetric Lewis acid catalysts may be realised.

c) The possibility of incorporating electron withdrawing groups onto the cationic imidazolium nucleus at C-2, C-4, or C-5 could yield yet another possibility in the modification of the Lewis acid design *ie.* to effectively draw more electron density from the imidazole center thus increasing the catalyst's ability to bind to a substrate *via* the inductive or resonance effects of that group.

As already discussed, there are many methodologies at the disposal of the synthetic organic chemist to create n,n-imidazolium salt compounds. However, a number of synthetic strategies for the synthesis of 1,3-ferrocenymethylimidazolium salts was needed. The initial aim of this research, was to prepare a series of 1-ferrocenylmethyl-3-alkylimidazolium salts **(96)** by a number of routes and then use these routes to create a series of similar salts, but which have electron withdrawing groups present on C-2, C-4, or C-5 of the imidazolium ring.

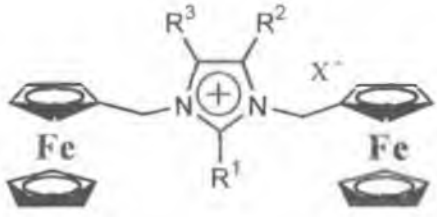


R^1, R^2, R^3 = Electron withdrawing group(s)

X = I⁻, PF_6^- n = C_1,C_2,C_3, etc.

(96)

Another possibility was to investigate the synthesis of cationic imidazolium salts containing two ferrocene units **(97)**, again attempting to incorporate electron withdrawing groups into the imidazolium ring.



R^1, R^2, R^3 = Electron withdrawing group(s)

X = I⁻, PF_6^-

(97)

The attractiveness of having two 'pendant' ferrocenyl moieties around the cationic imidazolium centre was first realised by Bildstein.[22] On combining imdazolium/benzimidazolium salts containing two ferrocene units with tungsten, platinum, and mercury to form their respective carbene complexes, the x-ray crystal structures of these complexes showed that the bulky ferrocenyl groups could effectively shield the central metal core. An example of these structures is given in Figure 6 , a metal carbene complex of **(79)** and palladium(II) salts.

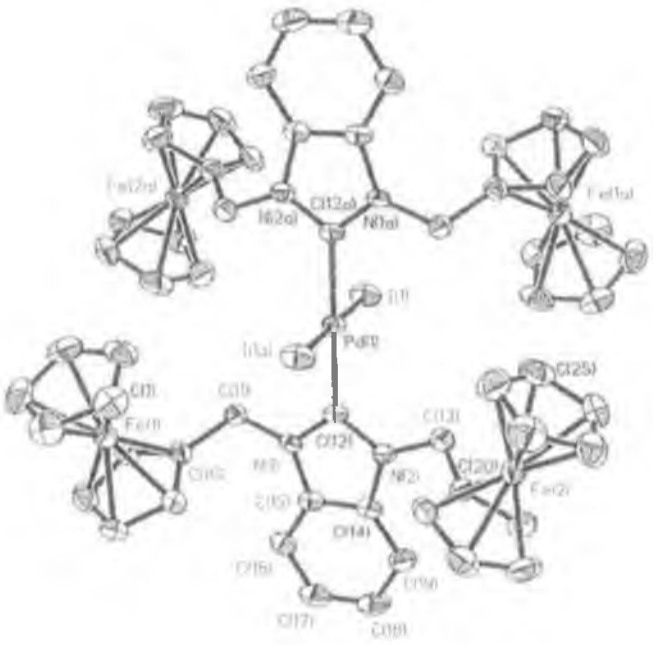


Figure 6

These findings, when looked at from a Lewis acid viewpoint, are quite significant, in that the contribution of the two ferrocene groups to the the Lewis acid capability of the imidazolium nucleus could also be explored.

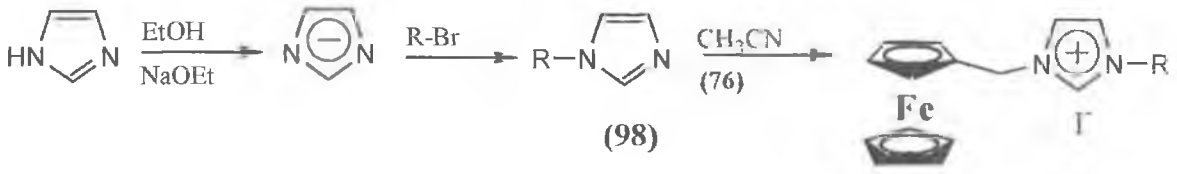
The n,n-dimethylamino-methylferrocene methiodide salt **(76)**[60] was chosen as a suitable intermediate for the incorporation of the ferrocenyl moiety into a cationic imidazolium nucleus.

What makes this compound so useful as a starting material is its relatively facile synthesis and high yield, and the fact that the crude product can be used without further purification. The compound also possesses the quaternary amino group - $N^{+}Me_3$ that functions as a very good leaving group in a S_N2 reaction. Nucleophilic displacement occurs *via* the nitrogen atoms in various substituted imidazoles.

During the course of this research it was noted that Bildstein[22] had already developed a synthesis for ferrocenylimidazolium systems but reported that the yields of ferrocenylimidazolium salts were inferior compared to that of benzimidazolium ferrcocenyl salts, hence most of his work was concerned with the latter. Using this reference and other established synthetic protocols as a starting point the following high yield syntheses were developed.

2.2 1-Ferrocenylmethyl-3 Alkylimidazolium Iodide Salts

Attempts to make the 1-alkylferrocenylimidazolium iodide salts were carried out by the following route (Scheme 46).



(98)

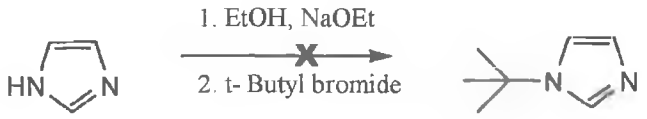
(99) R = Me
(100) R = Et
(101) R = Pr
(102) R = Bu

Scheme 46

The first step of the synthesis of unsubstituted alkylimidazolium salts was to make the appropriate 1-alkylimidazole precursors **(98)** by a procedure based on a paper by Bonhotes *et al.* [11] Imidazole is dissolved in ethanol, treated with sodium ethoxide to deprotonate the N-1 nitrogen, followed by treatment with an appropriate alkyl bromide to yield the desired product. The straight chain n-alkyl halides C_1 to C_4 posed no discernible synthetic problems by this method, and indeed both 1-methyl and 1 –butyl imidazole can be purchased in pure form.

The route was further extended to include the possibility of having a tertiary alkyl chain present in the alkyl ferrocenylimidazolium salt series. A number of attempts were made at preparing the 1-*tert*-butylimidazole precursor **(103)** using 1-*tert*-

butylbromide, but reaction attempts were unsuccessful and the analysis of the crude product obtained indicated only the prescence of the sodium salt of imidazole. From these observations it was inferred that the S_N2 process was now being dominated by a unimolecular S_N1 reaction between the generated tertiary alkyl carboanion and the reaction solvent to give a volatile ether side product, *tert*-butyl ethyl ether **(104)** as shown in Scheme 47.



(103)

(104)

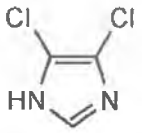
Scheme 47

A search of the literature gave syntheses for 1-*tert*-butylimidazole[68,69] but these routes were found to be multi-step in nature, and/or with poor yields of the final product resulting. As the initial aim of this work was to develop facile high yield syntheses for ferocenylimidazolium salts, it was therefore decided to concentrate solely on the preparation of straight chain n-alkylimidazoles.

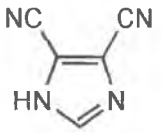
For synthesis of the subsequent 1-ferrocenylmethyl-3-alkylimidazolium salts, each n-alkyl imidazole was refluxed with a one mole equivalent of **(76)** in acetonitrile, over a period of 48 hours, to give the desired products in very good yields ranging from 60-85%. These yields were found to be much higher than previously reported.[22]

2.3 1-Ferrocenylmethyl-3-Alkylimidazolium Iodide Salts with Electron Withdrawing Groups on C-2,C-4, and C-5 of the Imidazole Ring

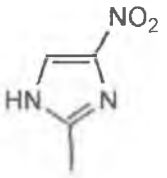
The alkylation of commercially available 4,5-dichloroimidazole **(105)**, 4,5-dicyanoimidazole **(106)**, and 2-methyl-5-nitroimidazole **(107),** was attempted using ethyl bromide.



(105)

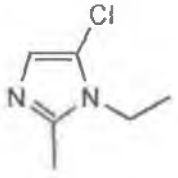


(106)



(107)

Alkylation of 4,5-dichloroimidazole and 2-methyl 5-nitroimidazole proceeded easily, as both are readily soluble in ethanol. Treatment of 4,5-dicyanoimidazole with sodium ethoxide resulted in the formation of its sodium salt which was not subsequently treated with ethyl bromide in view of earlier findings in Section 2.2.
A search through commercial reagent catalogues also yielded a useful alkylimidazole precursor in the form of 1-ethyl 2-methyl 5-chloroimidazole **(108)**.

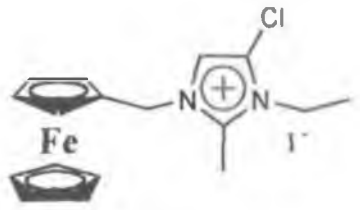


(108)

This compound proved useful in that it had an electron-withdrawing group present at C-5 and was already alkylated at N-1 with an ethyl group. It was also interesting to see what effect the chloro substituent, and indeed the additional methyl group on the imidazolium ring, would have on the Lewis acidity properties (see Chapter 3 of this thesis) of its corresponding ferrocenylimidazolium derivative.

Subsequent reaction of the 1-ethyl derivatives of 4,5-dichloro and 2-methyl 5-nitroimidazole with **(76)** in acetonitrile did not yield the desired substituted alkylferrocenylimidazolium salts. ^{1}H NMR analysis of the crude products obtained from these trial reactions showed only the ferrocene methiodide salt starting material present. It was assumed that failure of these reactions was due to the electron withdrawing effects of the chloro and nitro groups on the alkylimidazole precursors, either from inductive or resonance effects. These effects could subsequently influence the nucleophilic attacking power of the lone pair electrons on N-3 when reacted with **(76)**.

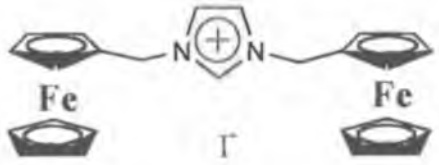
However, the synthesis of the ferrocenyl salt containing the 1-ethyl 2-methyl 5-chloro imidazolium centre **(109)** proved to be successful with a product yield of 83%, possibly due to the net contribution of the alkyl groups to electron density in the imidazole ring.



(109)

2.4 Preparation of a 1,3-Di(Ferrocenylmethyl) Imidazolium Iodide Salt

A different approach to making ferrocenylimidazolium salts, whereby two ferrocene units are present on N-1 and N-3 of the imidazolium nucleus, was attempted. These bis-ferrocenylimidazolium salt systems, of which 1,3-di(ferrocenylmethyl) imidazolium iodide **(110)** was prepared, could also be useful as Lewis acid catalysts.

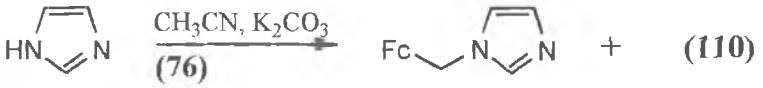


(110)

The methods employed were as follows.

2.4.1 Deprotonation of Imidazole

Based on observations made from the preparation of the 1-alkyl ferrocenylimidazolium salts, the deprotonation step of imidazole was used in the formation of 1-ferrocenylmethylimidazole **(111)**. This precursor could then be reacted with another mole equivalent of **(76)** to yield the desired 1,3-(diferrocenylmethyl) imidazolium iodide salt **(110)** as in Scheme 48.



(111)

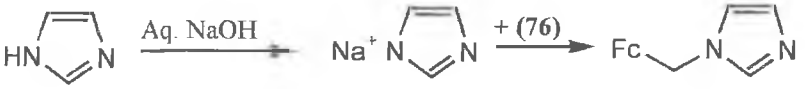
Scheme 48

It was decided to use a milder basic reagent for de-protonation of imidazole *via* the use of potassium carbonate as opposed to sodium ethoxide , and give a longer reflux time to investigate the possibility of exclusively forming **(110)** in a one-pot reaction.

^{1}H NMR analysis of the resulting oily product indicated the presence of a diferrocenyl moiety based on the observed magnitude of the integration ratio of the cyclopentadienyl proton signals. Given previous literature observations[11] of the insolubility of cationic imidazolium salts in 1,1,1-trichloroethane, an excess of this solvent was added to this crude oil to yield **(109)** as a yellow solid. Subsequent removal of the 1,1,1-trichloroethane by rotary evaporation from the resultant filtrate yielded the initially desired 1-ferrocenylmethylimidazole precursor **(111)**. The advantages of this synthetic route are obvious in that the formation of two potentially useful ferrocenylimidazolium compounds is now possible, and more importantly these can be obtained without further purification.

2.4.2 Imidazole Sodium Salts

Using the formation of 1-ferrocenylmethyl tetrazoles as a starting point,[58] the sodium salt of imidazole **(112)** was prepared by reacting an aqueous solution of imidazole with sodium hydroxide. Reaction of the imidazolium salt with the ferrocene methiodide salt **(76)** predictably gave the exclusive formation of 1-ferrocenylmethylimidazole **(111)** (Scheme 49).



(112) **(111)**

Scheme 49

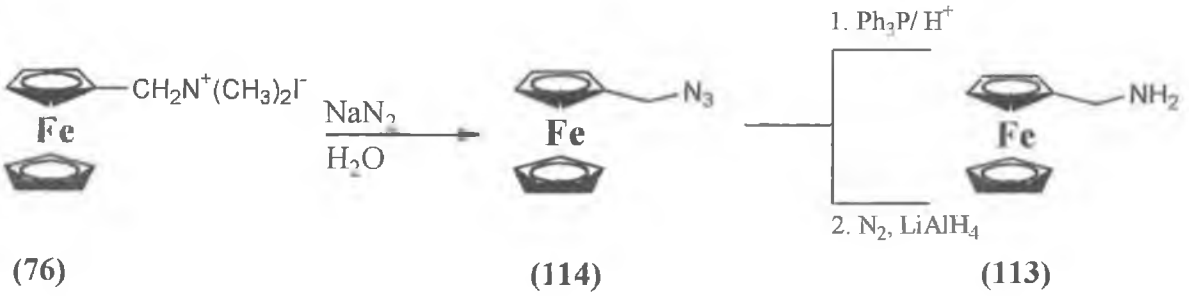
Further reaction of **(111)** with another mole equivalent of **(76)** gave the desired 1,3-di ferrocenylmethylimidazolium iodide salt **(110)** on work up.

2.4.3 Ring Condensation with 1-Ferrocenylmethylamine

Methods involving the production of imidazolium salts from primary amines and α-dicarbonyl compounds,[21,23] gave another possible route for the synthesis of **(110)**. Firstly the precursor, 1-ferrocenylmethylamine **(113)** had to be prepared.

(113)

Two possible routes were employed. Both routes used the easily prepared 1-ferrocenylmethyl azide **(114)**[70] as a starting material, which in turn was prepared by nucleophilic substiution of ferrocenylmethiodide salt with sodium azide (Scheme 50).

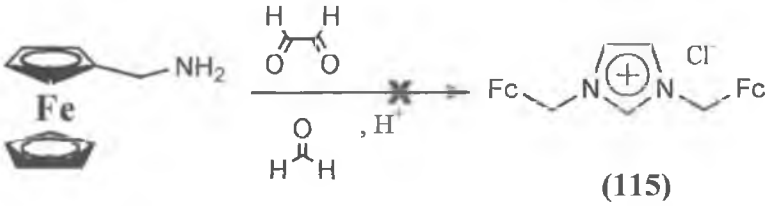


(76) **(114)** **(113)**

Scheme 50

The azide group of **(114)** is readily reduced by the use of lithium aluminium hydride, or by a Staudinger reaction using triphenylphosphine,[71] to give **(113)** in reasonable yields.

Using Arduengo's method,[19] two mole equivalents of 1-ferrocenylmethylamine were reacted with formaldehyde and glyoxal, using concentrated hydrochloric acid as a catalyst, in an attempt to form the cationic imidazolium ring center. Here the counter anion of the 1,3-di(ferrocenylmethyl) imidazolium salt by this route would be chloride **(115)** (Scheme 51).



(115)

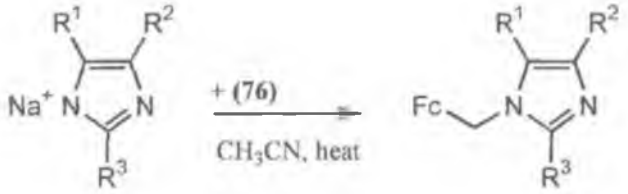
Scheme 51

Attempts to form **(115)** by this method were not successful. Addition of hydrochloric acid to the reaction mixture resulted in the immediate formation of a black precipitate, presumably due to the rapid formation of the ferrocenium cation , which was not subsequently characterised.

It was therefore decided to use the original approach of reacting **(113)** with glyoxal, formaldehyde, and ammonia in aqueous medium,[1] as an alternative synthetic route for making 1-ferrocenylmethylimidazole.

2.5 1,3-Di(ferrocenylmethyl) Imidazolium Iodide Salts with Electron Withdrawing Groups on C-2, C-4, and C-5 of the Imidazole Ring

The following routes were attempted to incorporate various electron withdrawing substituents into the diferrocenyl imidazolium salt molecule as in Scheme 52.

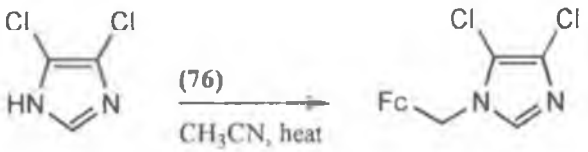


(116) $R^1 = CN$, $R^2 = CN$, $R^3 = H$
(117) $R^3 = CH_3$, $R^2 = NO_2$, $R^3 = H$

Scheme 52

The readily soluble sodium salts of 2-methyl 5-nitroimidazole and 4,5-dicyano imidazole were reacted with **(76)** in acetonitrile to yield the mono ferrocenylmethyl derivatives **(116)** and **(117)** in high yield.

Reactions were also attempted to incorporate halogens at C-4 and C-5 using commercially available 4,5-dichloroimidazole (Scheme 53).



(118)

Scheme 53

In this case, the monosubstituted ferrocenylimidazole derivative **(118)** was afforded. However, further reaction of all these derivatives with a further one mole equivalent of ferrocene methioidide salt **(76)** still yielded the corresponding monoferrocenyl starting material on work-up, even with prolonged reflux times. All of these observations were consistent with the previous attempts to incorporate electron-withdrawing groups into the imidazolium ring of the n-alkyl ferrocenylimidazoles.

2.6 Conversion of the Imidazolium Iodide Salts to Hexafluorophosphate Salts

Analysis of the crude products using standard thin layer chromatography was difficult to achieve because of their charged nature. These compounds tail severly on silica gel, possibly due to their interaction with residual silanol groups. A method developed by Bluhm[72] in which an ion pair is formed between silica pre-treated with a solution of sodium bromide, and the imidazolium salt, gave vastly improved sample spot resolution and definition. This method revealed that there was still a quantity of unreacted starting material present, which proved difficult to separate by standard flash chromatography techniques. Hence, for ease of purification and subsequent characterisation, it was found that anion exchange of the prepared iodide salts with ammonium hexafluorophosphate in acetone yielded the ferrocenylimidazolium PF_6^- salts in almost quantitative yield as crystalline solids. It was found that the PF_6^- salts were easier to re-crystallise and thus purify for subsequent characterisation.

The formation of the PF_6^- salt of 1-ferrocenylmethyl-3-butylimidazolium iodide **(102)** proved especially beneficial, as the iodide salt of this compound is an oil at room temperature, and hence quite difficult to handle.

CHAPTER 3

LEWIS ACIDITY OF THE FERROCENYLIMIDAZOLIUM SALTS

3.1 Introduction

The terms 'Lewis acid' and 'Lewis base', were made after discoveries by G.N. Lewis in 1923[73] and are extensions of the classical Bronsted-Lowry definition of acidity and basicity which applies to all compounds containing hydrogen. The Lewis classification of compounds applies to the movement of electrons in Lewis acid/base reactions, a Lewis acid being a compound capable of accepting an electron pair *via* a vacant, low energy orbital. Conversely, a Lewis base is a compound with a pair of electrons which are either unshared or in a π-orbital, which it can use in forming a covalent bond with a Lewis acid.[74] A Lewis acid base reaction may be represented by Scheme 54.

Scheme 54

In this example, boron triflouride acts as a Lewis acid because it has only six electrons in its outer shell and thus requires two more to achieve its octet whereas the ammonia is the Lewis base as it has two non-bonding electrons on nitrogen.

Lewis acids of the type BF_3, $AlCl_3$, $SnCl_4$, and $TiCl_4$ have been used as catalysts for different kinds of organic reaction where C-C bond formation occurs.[75] One of the first reactions to successfully employ these acid catalysts was the Diels-Alder reaction.

The Diels-Alder reaction[76] is one of the most useful carbon-carbon bond forming process in organic chemistry. It involves the [4 π s + 2 π s] cycloaddition of a diene and a dienophile **(119)** to give the adduct **(121)** and a generalized reaction scheme is given in Scheme 55.

(119) (120) (121)

Scheme 55

The reaction occurs in a single step through the cyclic transition state **(120)** in which two new carbon-carbon σ bonds are formed at the expense of two π bonds. This provides a significant driving force to the reaction, and allows it to proceed in a kinetically controlled yet irreversible manner.

Frontier molecular orbital theory has been used to explain several aspects of the Diels-Alder reaction, including regioselectivity, reactivity, and its catalysis by Lewis acids.[77]

In a purely thermal Diels-Alder reaction, the main factor to consider is the formation of the transition state where the lowest unoccupied molecular orbital (LUMO) of the dieneophile interacts with the highest unoccupied molecular orbital (HOMO) of the diene, or *vice-versa* (See Figure 7).

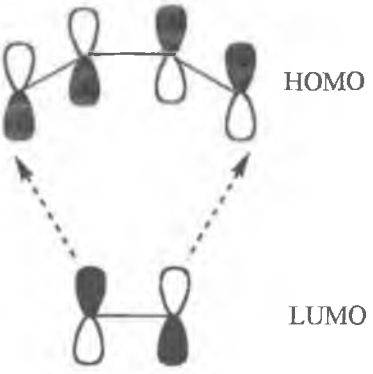
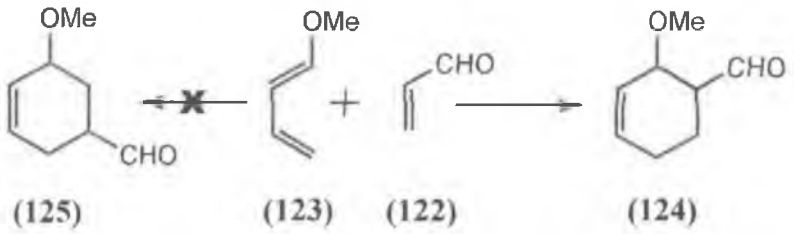


Figure 7

A typical Diels-Alder reaction is depicted in the following example (Scheme 56).[78]



(125) (123) (122) (124)

Scheme 56

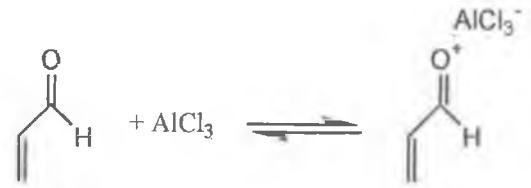
It is interesting to note that in this reaction, the carbonyl group of the dienophile acrolein **(122)**, by its electron withdrawing nature, lowers the energy of its LUMO. The electron donating groups of the diene, methoxybutadiene **(123)** conversely increases the energy of its HOMO. By the normalisation of the energy of the frontier molecular orbitals, overlap becomes more likely with a consequent increase in reactivity.

The regioselectivity of the above example is apparent in the formation of the 'ortho' adduct **(124)** as opposed to the 'meta' adduct **(125)** which can also be explained by frontier molecular orbital theory. The manner in which the unsymmetrical dienophile adds to an unsymmetrical diene is determined by the size and sign of the atomic orbital coefficients[77] of the terminal reacting atoms in each molecule.

The reaction can also be modified to such an extent that not only can C-C occur but that the diene or dieneophile may contain a heteroatom, which can lead to possible synthetic routes for heterocyclic ring systems.

As mentioned earlier, the reactivity and selectivity of the Diels-Alder reaction is greatly improved by use of a Lewis acid catalyst. In terms of frontier molecular orbital theory, the co-ordination of the Lewis acid to the dienophile *via* Lewis acid/base interactions, effectively reduces the energy of the dienophile's LUMO to allow even greater orbital overlap with the HOMO of the diene in the transition state. Regioselectivity is also increased in the catalysed reaction because co-ordination of the Lewis acid will reduce the orbital coefficient of the dieneophile's terminal carbon to which the electron withdrawing group is attached. As an example, acrolein **(126)**

forms a salt **(127)** with the Lewis acid $AlCl_3$ and it is this salt which is the more active and regioselective dienophile when used in a Diels Alder reaction (Scheme 57).

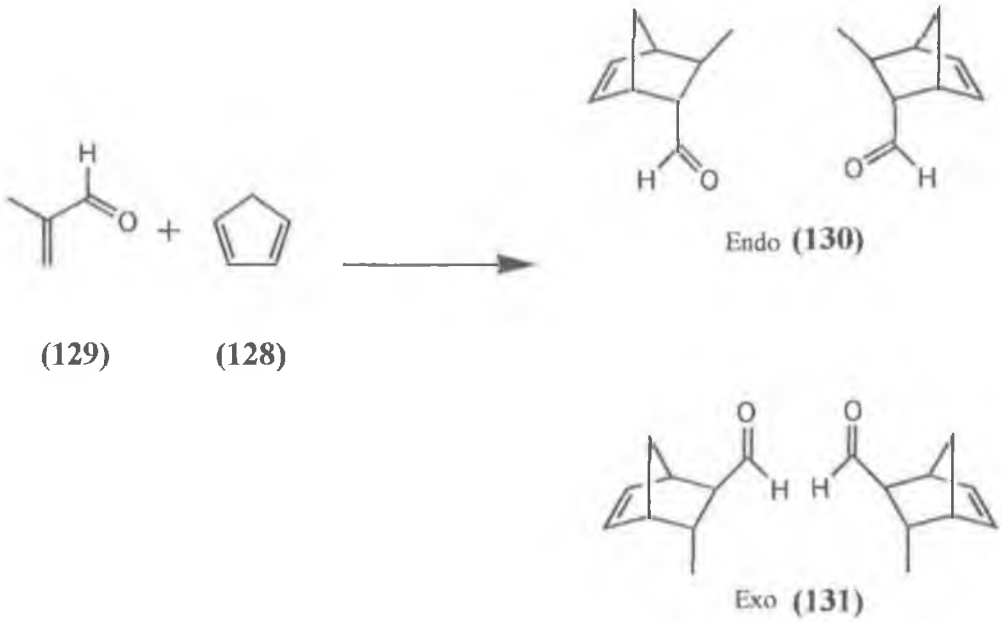


(126) **(127)**

Scheme 57

An early example of the effect of Lewis acids in the Diels-Alder reaction was reported in 1960. Yates and Eaton[79] reacted anthracene and maleic anhydride in the presence of $AlCl_3$ to yield a completed reaction in minutes. They predicted that the same reaction would take 4800 hr to complete at room temperature without a Lewis acid catalyst.

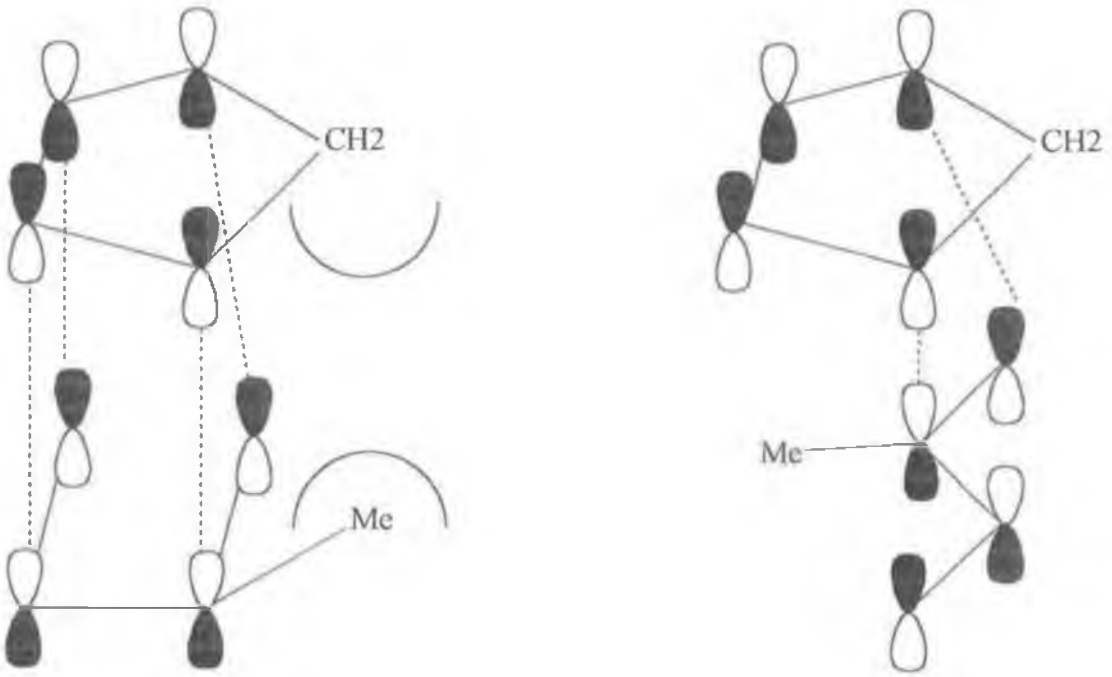
The prepared ferrocenylimidazolium compounds were evaluated as potential Lewis acid catalysts by investigating the Diels-Alder reaction between cyclopentadiene **(128)** and methacrolein **(129)** as illustrated by Scheme 58.



(129) **(128)**

Scheme 58

For each reaction there are four possible adduct products, also referred to as endo **(130)** and exo **(131)** diasteroisomers. In this Diels-Alder reaction, the predominately exo product is formed when methacrolein is used because of the adoption of best frontier orbital overlap in the transition state. Figure 8 shows the transition state possibilities for the endo and exo products.



Unfavoured (endo)

Favoured (exo)

Figure 8

The methyl group of the methacrolein sterically interacts with the methylene group on the cyclopentadiene in the case of the endo transition state hence making this reaction pathway unfavourable.

Even though Lewis acid co-ordination should reduce the orbital coefficients of the methacrolein and thus reduce the steric interactions in the endo transition state, this is not the case in practice as steric inhibition can still occur. Hence the exo transition state is enhanced even further by Lewis acid co-ordination thus favouring more rapid consumption of the dieneophile in the formation of exo product.

3.2 Experimental Procedure

The Diels-Alder reaction described above was carried out a low temperatures to ensure that the adduct formed was due to the presence of the Lewis acid catalyst in the reaction. A control reaction was also performed in which the catalyst was absent, to further prove that the catalyst was solely responsible for the reaction to proceed.
The use of the cyclopentadiene and methacrolein Diels-Alder system yields an adduct which is easily recovered from the reaction mixture by silica gel flash chromatography and the endo:exo ratios were determined by ^{1}H NMR. The dichloromethane solvent was carefully removed at room temperature, as the resulting adducts from this reaction were quite volatile. The adduct could be seen on TLC by development with a mobile phase of petroleum ether 60-80/dichloromethane, followed by exposure of the plate to iodine vapour. On the TLC system described, the methacrolein adduct had an R_f of 0.48. There was also another spot present with an R_f of 0.93 and this was found to be unreacted cyclopentadiene. All the catalysts tested were readily soluble in dichloromethane, which made the resulting Diels-Alder reaction products easy to apply to a flash chromatography column without prior filtration to remove the catalyst.

The molar ratio of diene: dienophile: catalyst employed was 5:1:0.2 respectively. Using these reactant proportions it could be determined whether the reactions were catalytic or purely stoichiometric. A large excess of diene as opposed to the dieneophile will introduce a rate-limiting factor *ie.* the formation of a catalyst/dienophile transition state which will in turn allow the catalyst to have the greatest influence over the rate of reaction.

The ^{1}H NMR of the methacrolein adduct shows two singlet aldehyde peaks at 9.67 and 9.39 ppm for the exo and endo products respectively. The integral sizes of these peaks were used as a basis for determining the exo:endo ratios.

3.3 Results and Discussion

As discussed in chapter 2 of this work, the initial rationale behind using ferrocenylimidazolium salts as Lewis acid catalysts was to exploit the electron deficient quaternized imidazolium moiety as the Lewis acid centre for subsequent co-ordination to the dienophile in the Diels-Alder reaction. As the N-1 and N-3 of the imidazole ring can be substituted with varying alkyl chain length and with one or two ferrocene moieties, the variation of catalyst 'turnover' *ie.* the magnitude of adduct yield, can be investigated.

The adduct yields can possibly be influenced by the interaction between the substrate and catalyst followed by the repulsion of the catalyst by the adduct. The magnitude of binding between the catalyst and product will influence the turnover of the catalyst and should be relatively low if product yields are to remain high.

All the ferrocenylimidazoloium iodide salts were subjected to the same experimental procedure, and the results are summarised in Table 8.

Table 8

R-Ferrocenylimidazolium iodide salt.	**% Yield of adduct**	**Endo: Exo Ratio**
1-Methyl **(99)**	32	29 : 71
1-Ethyl **(100)**	67	10 : 90
1-Propyl **(101)**	72	11 : 89
1-Butyl **(102)**	45	18 : 82
2-Methyl 3-ethyl 5-chloro **(109)**	95	13 : 87
1,3-diFerrocenyl **(110)**	56	15 : 85
Control reaction	-	-

It can be seen from the above table that all the catalysts tested exhibited varying degrees of Lewis acid catalyst activity in the methacrolein/cyclopentadiene Diels-Alder reaction. With the exceptions of **(99)** and **(102)**, adduct yields are quite significant, particularly in the case of **(109)**. The imidazolium iodide salt **(109)** could have given better yield results due to the inductive effect of the chlorine atom present at C-5.

These yields improve on Howarth's initial findings, but it is worth noting however when the salts were tested using crotonaldehyde as the dienophile under similar reaction conditions, no endo/exo products were formed. This could be due to magnitude of binding of the catalyst to the crotonaldehyde substrate, or the lack of sufficient repulsion between the adduct and the catalyst during the course of the Diels-Alder reaction. It may also be the case that conformational processes are occurring which may inhibit the diene from approaching the crotonaldehyde/catalyst complex easily.

In an attempt to rationalise the results, molecular models of the catalysts were constructed from a molecular orbital perspective using the "SPARTAN" computer molecule programmes to generate the LUMO of the catalyst. An example of this is given below for the ferrocenylimidazolium salts **(101)** and **(110)**.

Figure 9. Iodide salt (101) top-view

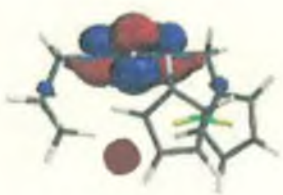
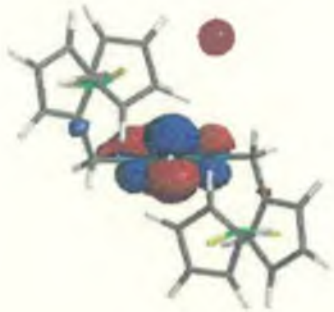


Figure 10. Iodide salt (101) side view



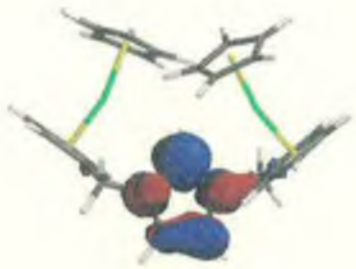
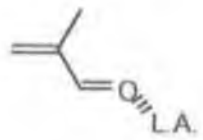


Figure 11. Iodide salt (110) side view. **Figure 12. Iodide salt (110) top view.**

SPARTAN is an ab initio/semi-empirical/molecular mechanics modelling software package that was used for all the calculations. It was installed on a Silicon Graphics O2 workstation, MIPS 10000 processor, 128 MB RAM running under IRIX 6.3.
On model building the molecules of interest, a molecular mechanics optimisation, using the Merck Molecular force field (MMFF) was performed in order to obtain one of the possible conformations for each imidazolium iodide salt. This was followed by a Monte Carlo conformation search so as to efficiently sample the available conformational space. This procedure should yield the lowest energy conformation of the molecule. In order to visualise the LUMO of all the ferrocenylimidazolium salts (See Appendix A.) a semi-empirical calculation was then needed. Molecular mechanics calculations do not deal with the electron distribution around a molecule whereas semi-empirical calculations, by solving an approximation of the Schrödinger equation, do. This yielded the images displayed in Figures 9 to 12. This could help in the identification of possible co-ordination sites for the formation of the catalyst-dieneophile complex.

The interaction between the Lewis acid catalysts and methacrolein should occur *via* co-ordination to the lone pair of electrons on the carbonyl group of methacrolein furthest from the α-methyl group (Figure 13), which dictates the formation of the predominately exo product.



L.A. = Lewis Acid

Figure 13

It has been reported[80] that the structure of the Lewis acid-carbonyl complex in these reactions is very much dependant on the **a)** the mode of co-ordination of the dienophile's carbonyl oxygen to the catalyst, which can occur *via* σ bonding between the oxygen lone pairs and the Lewis acid centre or *via* π bonding between the carbonyl double bond and the Lewis acid centre.(Figure 14.)

σ-bonding mode **π-bonding mode**

Figure 14

Both of these bonding modes will thus have an influence on **b)**, the geometrical location of the Lewis acid itself which can be in-plane bent or in-plane linear to the dienophile (Figure 15)

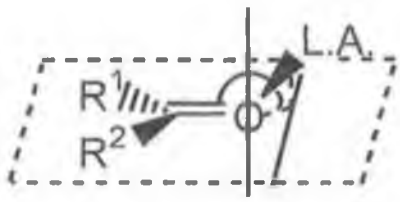
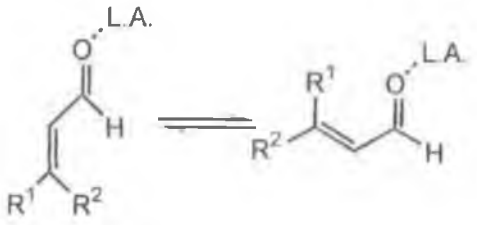


Figure 15

and **c)**, the ground state conformational preferences of the groups adjacent to the carbonyls R^1 and R^2, as dictated by the following equilibrium (Scheme 59).



s- *trans* s- *cis*

Scheme 59

This latter aspect has been of much interest in recent times[77] where there is a possibility of s-*cis* or s-*trans* conformers in α,β–unsaturated carbonyl compounds, such as methacrolein or crotonaldehyde.

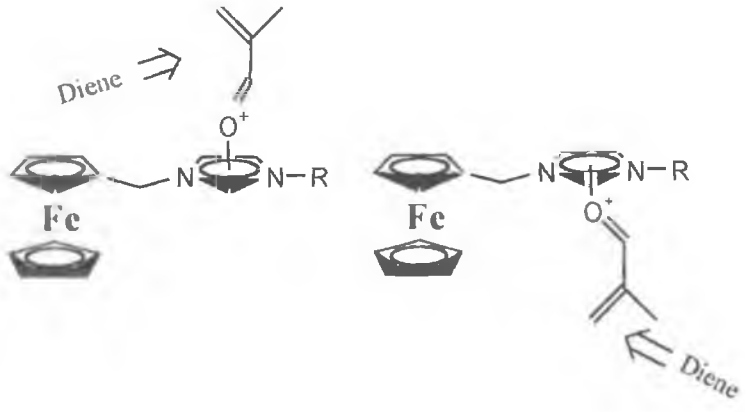
When the conformational aspects of each catalyst was looked at, there appeared to be a tentative relationship between yield of adduct and alkyl chain length assuming that it is the imidazolium cationic centre which is playing the role of the Lewis acid catalyst. The alkyl chain length clearly influences the conformation of the ferrocene moiety that may effectively direct the approach of the diene in the Diels-Alder reaction. The length of the alkyl chain may be significant in the fine tuning of the system from a catalytic turnover viewpoint. The presence of the iodide anion in these catalysts will also contribute steric shielding by virtue of the magnitude of its Van der Waal radius (R = 2.16 angstroms).

The presence of the chlorine atom in **(109)** does seem to have an effect on the overall electron density of the catalyst, thus pointing to the possibility that the electron withdrawing group could play a role in the catalyst's ability to bind to the dienophile.

The inclusion of two ferrocene groups **(110)** is also interesting. The ferrocenyl groups in this catalyst are staggered when modelled, and this finding was confirmed in previous publications.[22] The ferrocene moiety represents a quite bulky group with unique spatial requirements due to its cylindrical shape, and this steric requirement coupled with the presence of the iodide anion could make for a highly directed approach of the diene to the dienophile/catalyst complex.

Indeed, the actual mode of catalysis in the ferrocenylimidazolium systems could be occuring by two different modes ie. co-ordination of the dienophile directly to the imidazolium cationic centre, or *via* the ring proton at C-2 on the imidazolium center.

There are numerous examples in the literature of Lewis acid catalysts based on cationic complexes, particularly those derived from cationic alkali-metals[81], and cationic 'half-sandwich' metallocene salt systems.[82]
A pictorial representation of what may be occurring in of these systems would suggest that the cationic imidazolium centre could possibly bind to the methacrolein in the following way (Scheme 60)



Scheme 60

It is also well established that the proton on the electron deficient C-2 carbon of the cationic imidazolium ring system plays a significant role in the hydrogen bonding of ionic liquids[83] and more recently in the formation of anionic receptors[84] by means of C-H•••X^- hydrogen bonding interactions. More recent evidence of C-H•••O bonding between cationic thiazolium ring systems and proteins, presented by Musah and co -

workers[85] has revealed that these bonding interactions may vary considerably due to the C-H polarity of hydrogen atom at the C-2 position of the cationic heterocyclic ring. It is interesting to note that the molecular orbital diagrams of the LUMO of each catalyst consistently displayed a large orbital lobe present on the proton of the imidazolium ring at C-2, and to a lesser degree the C-4 position. This suggests that the proton on C-2 could possibly be acting as the Lewis acid centre for co-ordination to the dienophile in the catalytic reaction as opposed to the cationic imidazolium centre alone, as previously thought.[39] There is also the possibility that the proton on the C-4 position may present a second site for co-ordination of another molecule of dienophile which in turn may help to displace the formed adduct at C-2, leading to greater catalytic turnover.

3.4 Conclusions

From the initial outset of testing the fererocenylimidazolium iodide salts do display Lewis acid catalytic ability but the actual mode of catalysis is not clear. The endo:exo ratios and yields for all catalysts indicate that either the proton on the imidazolium C-2 could be due to the Lewis acid capabilities of the compounds or, in the case of **(109)**, the cationic imidazolium center alone. Investigations could be carried out *via* ^{1}H NMR studies of the dienophile/catalyst complexes in solution. However the failure of the catalysts in the crotonaldehyde/cyclopentadiene reaction may limit their use somewhat. Hence other dienophiles and indeed other reactions which are catalysed by Lewis acids could be investigated such as the –ene reaction[86] or Claisen rearrangements.[87]

With the inclusion of ferrocene in the catalytic design, it may be possible to exploit the central and planar aspects of this molecule in the synthesis of chiral ferrocenylimidazolium salts. There is also the possiblity to use the ferrocenium ion as another potential binding center, thereby leading to the potential of creating a new range of asymmetric Lewis acid catalysts.

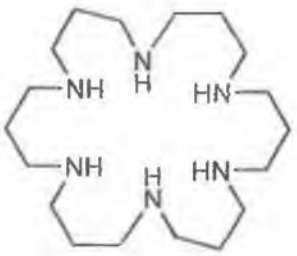
CHAPTER 4

THE FERROCENYLIMIDAZOLIUM SALTS AS POTENTIAL ANION RECEPTORS

4.1 Introduction

Anions are known to play a very significant role in a wide range of chemical, environmental, and biochemical processes.[88,89] The development of receptor molecules, which can effectively bind and 'sense' these species, has become an area of considerable research interest in recent times.[90] Molecules which act as receptors for anionic species can be positively charged or neutrally electron deficient in origin, the anion being effectively bound to the receptor by electrostatic attraction or hydrogen bonding. Receptor molecules can be designed to selectively bind one target anion in the presence of other anionic species by exploiting physio-chemical properties of the target anion such as electronegative strength, size, conformation, and other chemical characteristics such as, for example, the pKa of 'acidic' anionic species *eg.* HPO_4^-, HCO_3^-, and HSO_3^-. Indeed, the conformational properties of the receptor molecule itself may influence the degree of selectivity of the receptor molecule and allow it to differentiate between one anionic 'guest' and another.

Initial research into the synthesis of these receptor molecules yielded classes of anion receptor such as crown ethers with Lewis acid centres,[91] ammonium quaternary salts,[92] and guanidines.[93] Macrocyclic molecules based on polyamines such as compounds **(132)** and **(133)** were first reported by Dietrich *et al.*[94]



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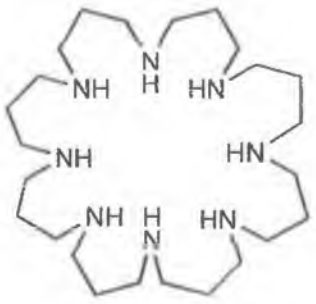
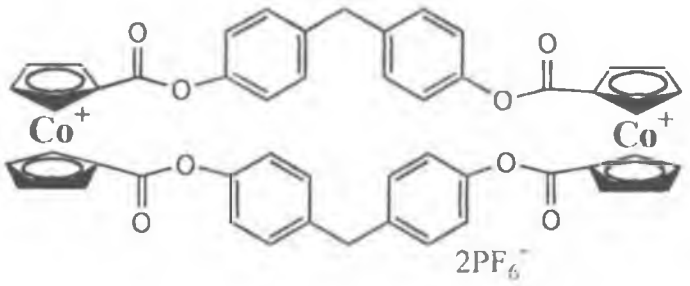


(133)

It is interesting to note that the above polyamine macrocycles exhibit strong anion binding properties *via* electrostatic host-guest interactions, when the amino groups are fully protonated.

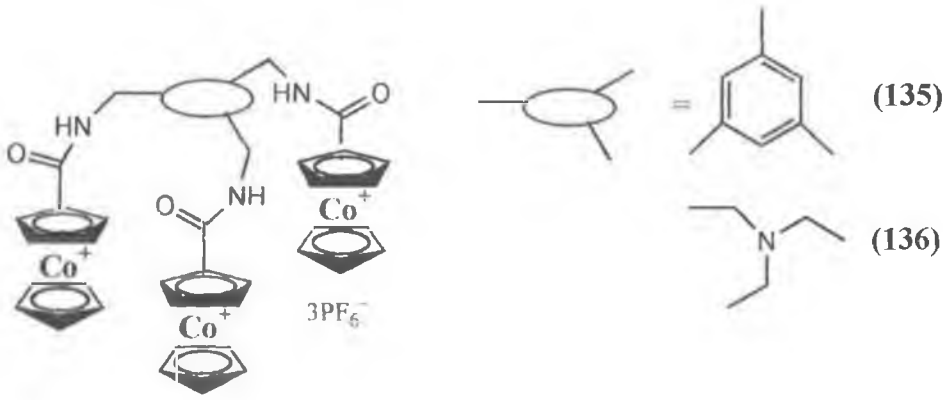
A further development in electrostatic receptor design was to realise the effectiveness of incorporating transition metals into the receptor molecule. In 1989 the first transition metal centered anion receptor **(134)** was reported by Beer and co-workers.[95]



(134)

The cobaltocenium moiety was found to interact electrostatically with a bromide anion, a phenomenon which could be observed *via* the cathodic wave shift of the cobaltocene/cobaltocenium electro-couple.

The incorporation of sites into anion receptors, which function *via* hydrogen bond host/guest interactions, has also been realised. Beer and co-workers reported that the combination of a metal unit as a Lewis acid, together with and amide N-H group as a hydrogen bond donor, are essential in the design of receptor molecules for anion recognition.[96] In 1992, Beer reported the synthesis, anion co-ordination and electrochemical studies of the novel acyclic anion receptors **(135)** and **(136)** containing a redox-active, pH independent positively charged cobaltocinium moiety and an amide N-H.[97]



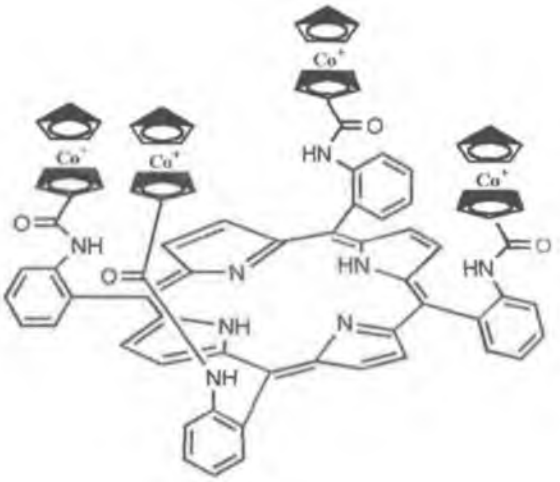
(135)

(136)

Beer found that the addition of varying amounts of tetrabutylammonium chloride to deuterated acetonitrile solutions of **(135)** and **(136)** resulted in remarkable shifts in the respective ^{1}H NMR signals of both receptors. In particular, it was noticed that the downfield shifts for the amide protons were of the order of δ = 1.28 ppm and 1.52 ppm respectively, on addition of a one mole equivalent of tetrabutylammonium chloride. It was suggested that a significant –CO-NH••••Cl^- hydrogen bonding interaction was contributing to the overall anion complexation process. Subsequent ^{1}H NMR titration studies suggested a 1:1 stoichiometric relationship with Cl^-, Br^-, and NO_3^- and the above receptors. It was also noted that a replacement of the amide proton with a methyl or methylene group in the receptor design gave no ^{1}H NMR shifts under analogous experimental conditions.

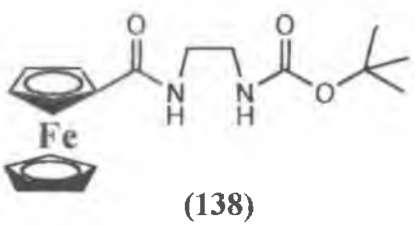
Thus it was shown that the receptors could bind anions through hydrogen bonding interactions between the amide protons, and electrostatic interactions with the positively charged cobaltocenium center. Subsequent work found that the strength of the binding of anions to this class of receptor was greatly enhanced by the hydrogen bonding effect.[98]

Beer's research led to the discovery of other receptor molecules that utilised the cobaltocenium moiety, which included receptors for the dihydrogen phosphate anion,[99] as well as novel receptor compounds based on porphyrins, such as receptor **(137)**.[100]



(137)

Neutral ferrocene receptor molecules containing amide moieties have also been used as anion receptor molecules, where the mode of anion binding is exclusively due to hydrogen bonding interactions. The absence of an electropositive iron metal centre may even provide better selectivity for different anionic species, with the option of oxidation of the ferrocene moiety to ferrocenium to further modify the selectivity of the receptor as required. Beer and co-workers synthesised simple amide-functionalised ferrocene derivatives such as **(138)** and **(139)** with a view to utilising them as electrochemical anion-selective redox sensors. [101,102]



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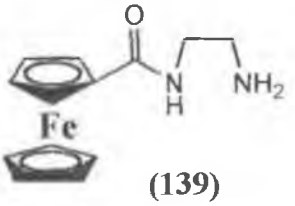


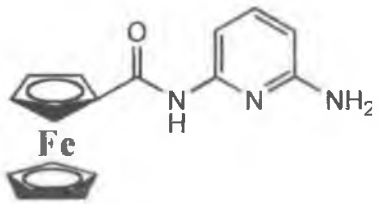
(139)

The inclusion of a neutral amine group into the receptor design **(139)** can also allow the receptor to function *via* hydrogen bonding or a combination of hydrogen bonding and electrostatic modes, pending on the nature of the anion guest. This may increase the selectivity of same. To illustrate this point, Beer found that receptor **(139)** gave a significant response to the HSO_4^- anion, due to protonation of the basic amine group by the acidic hydrogen sulfate anion. The di-negative sulphate anion thus produced

should have a high affinity for the receptor sites via subsequent hydrogen bonding. It is therefore possible that receptor **(139)** may also function electrostatically in this case. For simpler anions such as the halide anions, the receptor may function by hydrogen bonding alone (Figure 16).

Figure 16

Neutral acyclic **(140)** tripoidal **(141)** and calix{4}arene ferrocene receptors **(142)** were also discovered, which were also found to be useful as receptor compounds.[96] The three dimensional aspect of these receptors may further enhance the selectivity of these receptors by accounting for the steric considerations of the anion binding to them. For example, the novel molecular receptors **(141)** and **(142)** are capable of detecting $H_2PO_4^-$ in the presence of a ten-fold excess of HSO_4^- and Cl^- anions.



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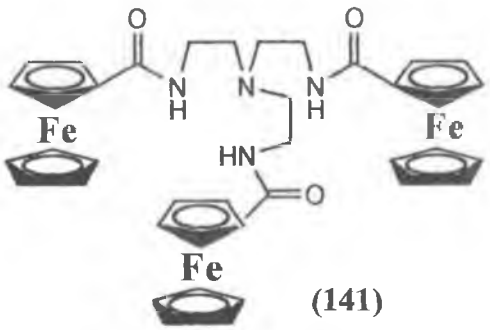

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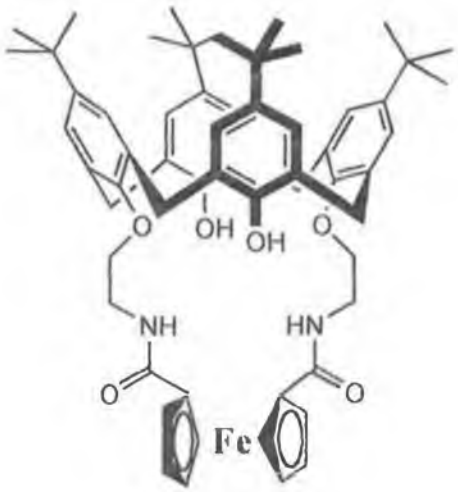
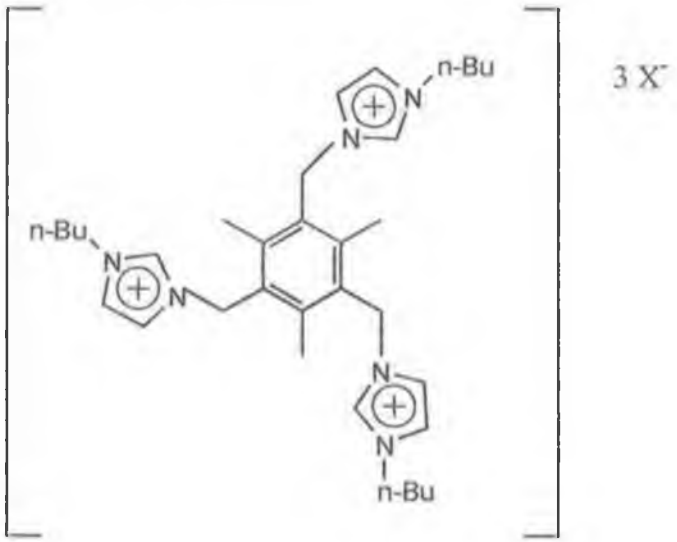


(142)

Recently, the imidazolium derivative 1,3,5-[tris(3-n-butylimidazolio)methyl]-2,4,6-trimethylbenzene **(143)** has been described by Sato and co-workers[84] as a new tripodal anion receptor molecule that possesses C-H••••X$^-$ (where X is a halogen) hydrogen bonding on the electron deficient C-2 of the imidazolium ring. This has been a significant finding in the field of imidazolium chemistry.



X = Br^-, PF_6^-

(143)

The molecule possesses three electron deficient imidazolium groups connected *via* a 1,3,5-trimethylbenzene 'spacer' molecule. It was found that ^{1}H NMR titration studies carried out in deuterated acetonitrile, CD_3CN, with the tetraethylammonium salts of the halides Cl^-, Br^-, and I^- lead to considerable downfield shifts (δ >1.3 ppm) of the C-2 proton signal of the imidazolium rings in the receptor.

Large association constants of the order of 75,000-7200 dm^3 mol^{-1} between the receptor and the various halide anions were also found, indicating the high binding degree between the receptor and the target anion.

Sato also proposed a possible structure for the halide anion/receptor complex, which is predominately, an all *syn* conformation, which could account for the high degree of selectivity of the receptor, for halide anions (Figure 17).

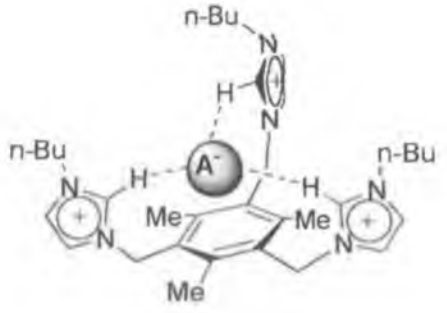
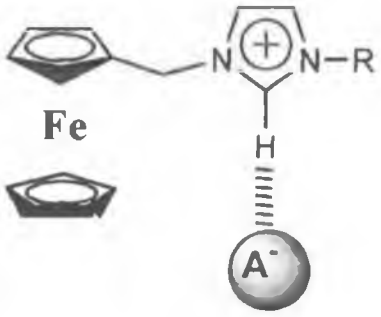


Figure 17

Sato's findings are significant in that they observe the electrostatic interactions between the imidazolium center and anions.

In the case of the ferrocenyl imidazolium salts, similar effects should be observed. The potential for the imidazolium moiety to bind anions could be possible *via* hydrogen bond formation at the proton on the C-2 carbon, as shown in Figure 18.



Hydrogen bonding mode

Figure 18

To investigate their potential as anion receptors, a ^{1}H NMR study was carried out for the various ferrocenyl imidazolium hexafluorophosphate salts, with the exception of 1-Ferrocenyl 2-methyl-3-ethyl-5-chloroimidazolium hexafluorophosphate salt **(109)**, as this compound has no proton available for hydrogen bonding on C-2.

4.2 Experimental Procedure

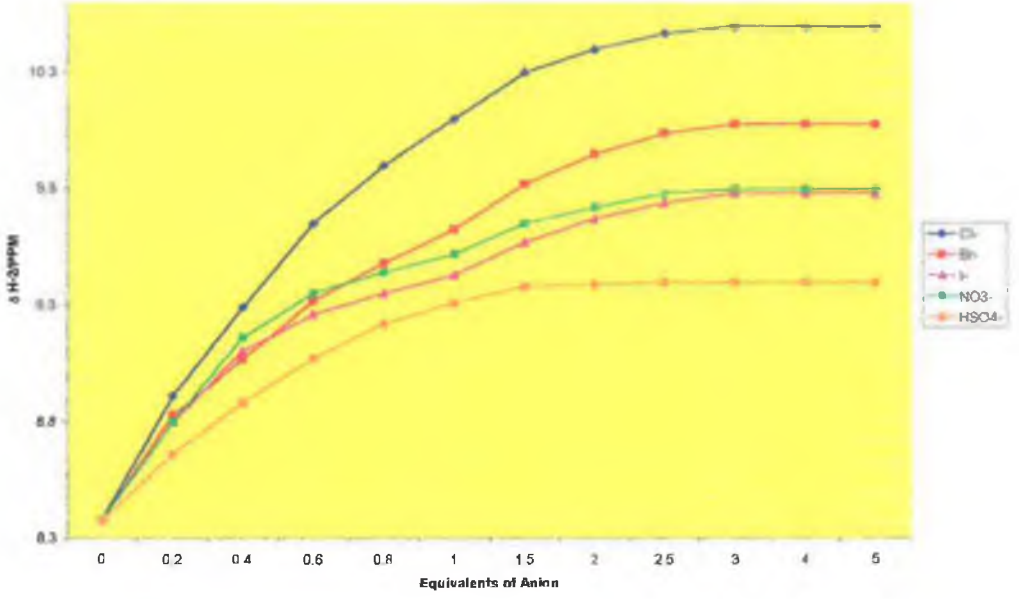
A 1 $x10^{-2}$ molar stock solution of each imidazolium hexafluorophosphate salt was prepared by weighing out an accurate amount of same and diluting to a volumne of $10cm^{3}$ using deuterated chloroform. Into a series of clean glass NMR tubes approximately $1.0cm^{3}$ aliquots of receptor was transferred with the aid of a micropipette. Each aliquot was then sequentially treated with zero to five mole equivalents of the solid tetrabutylammonium salt of the anion being studied.

The ^{1}H NMR spectra were recorded using a Bruker AVANCE series 400MHz spectrometer.

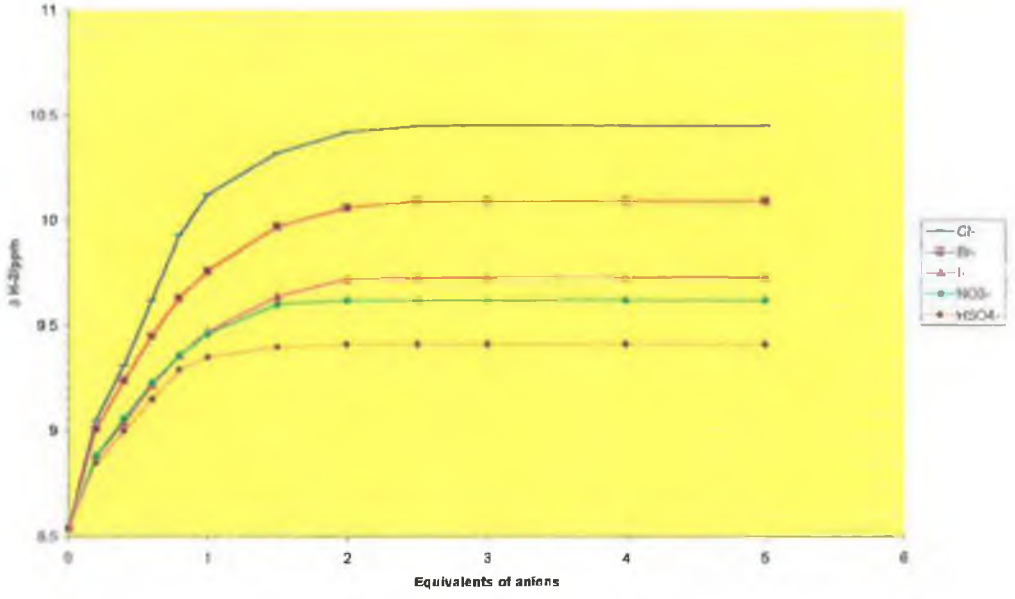
4.3 Results and Discussion

Each ferrocenylimidazolium hexafluorophosphate salt was subjected to the same experimental conditions, and the characteristic shift of the imidazolium C-2 proton was measured. The following series of titration curves were obtained for each receptor.

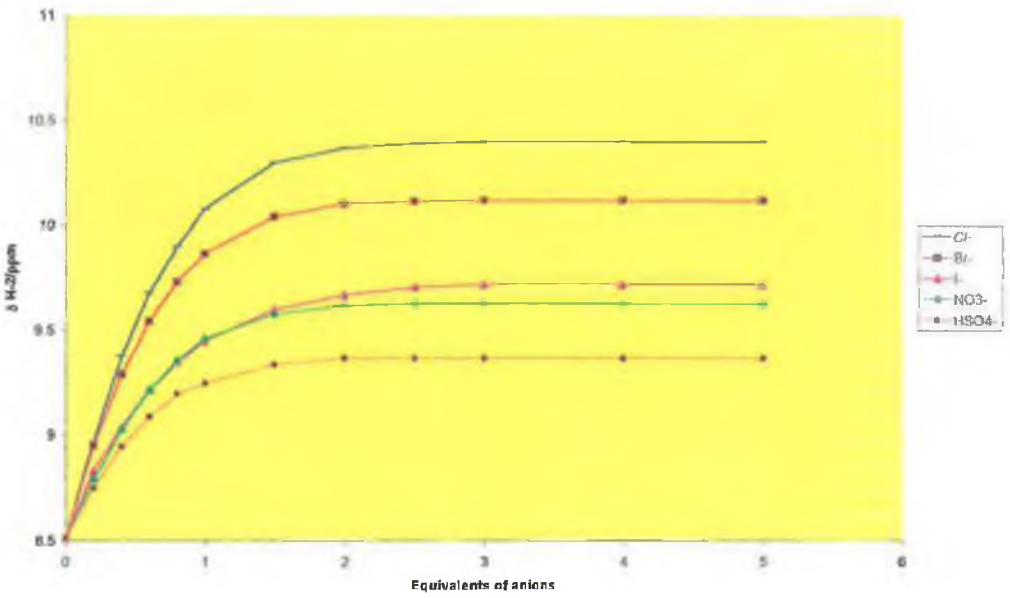
1-Ferrocenylmethyl-3-methylimidazolium hexafluorophosphate **(99)**



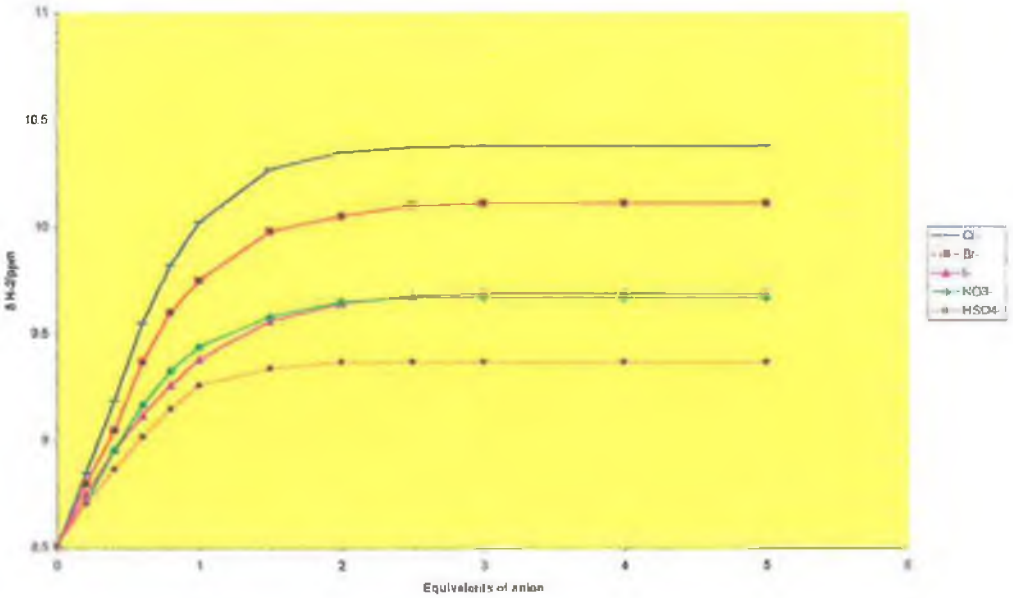
1-Ferrocenylmethyl-3-ethylimidaolium hexafluorophosphate **(100)**



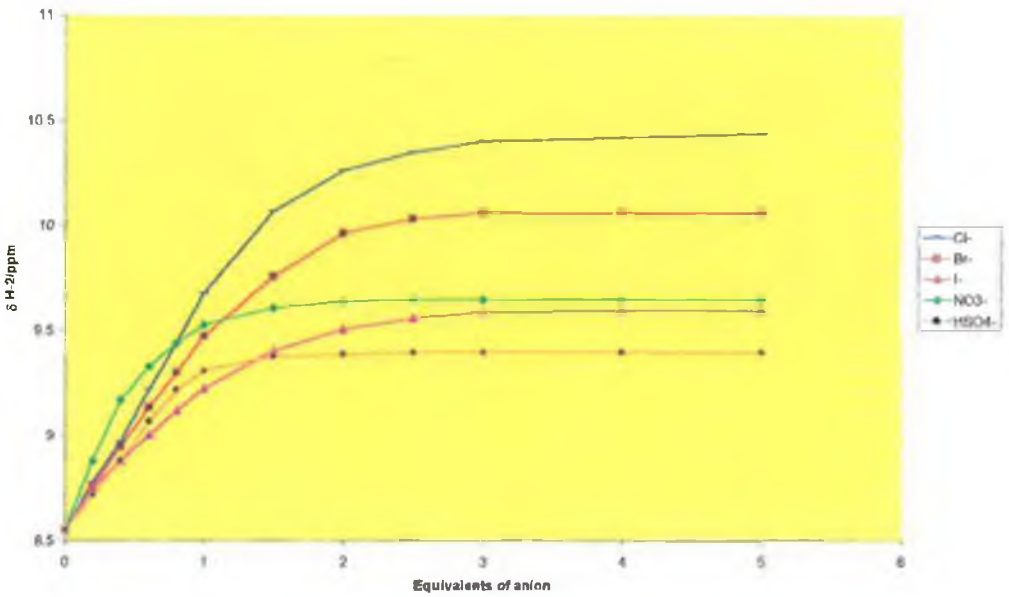
1-Ferrocenylmethyl-3-propylimidazolium hexafluorophosphate **(101)**



1-Ferrocenylmethyl-3-butylimidazolium hexafluorophosphate **(102)**



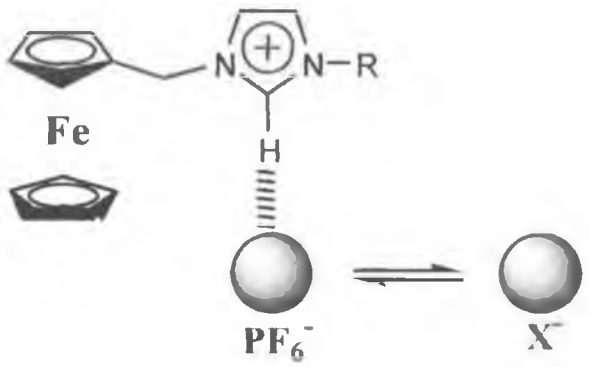
1,3-di(Ferrocenylmethyl)imidazolium hexafluorophosphate **(110)**



The above titration curves suggest a stoichiometry of 1:2 imidazolium salt: anion in the case of the anions Cl^-, Br^-, NO_3^-, and I^- for all of the receptors , and a stochiometry of 1:1 imidazolium salt:anion ratio for HSO_4^-, as evident in the characteristic changes of the downfield shift of the imidazolium C-2 proton signal. These shifts are indicative of hydrogen bonding interactions between the hydrogen atom on C-2 with the co-ordinated anion guest. Small differences in the proton signals of C-4 and C-5 were also seen, which may be indicative of some interaction of these protons in the binding process. In the case of receptor **(110)** the same results were observed, but a 1:1 salt: anion ratio is more defined for the NO_3^- anion. This could be due to a combination of steric effects exerted by the second ferrocenyl pendant in this salt or the overall conformation of the host/guest complex.

It was expected that the halide anion:imidazolium salt ratio should be 1:1 for all the receptors, and that the ^1H NMR titration curves would be clearly defined. A visual extrapolation of the curves to give a linear 'best-fit' would point to the evidence that all the receptors react in a 1:1 manner with the anions examined. It is also possible that the guest anions could be binding *via* a combination hydrogen bonding and electrostatic modes to the imidazolium centre as previously shown in Figure 16. The

lack of defined curves for the halide ions could also point to the possibility that the anion exchange process between the PF_6^- anion and the guest anion does not go to completion but rather an equilibrium process is occuring as shown in Scheme 61 *i.e* there could possibly be a degree of competitive interaction in the anionic exchange between halide/hexafluorophosphate anions, and the ferrocenylimidazolium moiety.



Scheme 61

4.4 Conclusions

The ^1H NMR studies clearly demonstrate that the prepared ferrocenylimidazolium salts have potential as anion receptors[62] but further investigations need to be carried out to precisely evaluate their effectiveness. X-ray crystallography studies of each receptor-guest complex should conclusively confirm the binding sites in each receptor, and this research work is ongoing. Also, electrochemical studies of the ferrocene/ferrocenium redox couple could be examined with a view to further determining the selectivity of each receptor to a given anion. The inclusion of ferrocene in the imidazolium salt design may serve as a molecular 'antenna' from an electrochemical viewpoint. This may realise the potential of ferrocenylimidazolium salts as possible 'sensor' molecules for the electrochemical detection of anionic species in solution.

CHAPTER 5

EXPERIMENTAL

5.1 Imidazole Derivatives

5.1.1 General Procedure for the Preparation of 1-Alkylimidazoles

Imidazole (16.70 g, 0.73 mol) was stirred in ethanol (100 ml) under nitrogen until all the solid had dissolved. Sodium ethoxide (18.40 g, 0.81 mol) was then added. The warm reaction mixture was stirred for 30 min and then the appropriate freshly distilled n-alkyl bromide (0.81 mol) was added dropwise over a period of 30 minutes. The reaction mixture was then heated to reflux temperaturere with stirring for 1h, during which time a white precipitate of sodium bromide was observed. The reaction mixture was then cooled to room temperature and filtered to remove excess sodium bromide. The excess solvent was removed by rotary evaporation to yield the desired compound which was purified by vacuum distillation.

The following compounds were prepared in the above manner.

1-Ethylimidazole[11] from 1-bromoethane as a colourless oil (8.93 g, yield: 42%), b.p. 30^0C /0.8 mBar. ^{1}H NMR ($CDCl_3$): δ 1.22 (t, J = 7.4 Hz, 3H, -CH_2CH_3), 3.76 (q, J = 7.4 Hz, 2H, -CH_2CH_3), 6.72 (s, 1H, Im H-5), 6.83 (s, 1H, Im H-4), 7.26 (s, 1H, Im H-2)

1-Propylimidazole from 1-bromopropane as a colourless oil (13.57 g, yield: 67%), b.p. 80^0C /0.8 mBar. ^{1}H NMR ($CDCl_3$): δ 0.71 (t, J = 7.4Hz, 3H, -$CH_2CH_2CH_3$), 1.57 (m, 2H, -$CH_2CH_2CH_3$), 3.67 (t, J = 6.9Hz, 2H, -$CH_2CH_2CH_3$), 6.70 (s, 1H, Im H-4), 6.83 (s, 1H, Im H-5), 7.24 (s, 1H, Im H-2)

5.1.2 1-Ethyl-4,5 Dichloroimidazole

4,5–Dichloroimidazole (5.07 g, 0.04 mol) (from Aldrich) was stirred in ethanol (30 ml) under nitrogen until all the solid had dissolved. Sodium ethoxide (2.80 g, 0.04 mol) was then added

and the warm reaction mixture stirred for 30min. Freshly distilled 1-bromoethane (4.46 g, 0.04 mol) was added dropwise over a period of 1h and the resulting solution was then heated to reflux temperature for 3h. The reaction mixture was cooled to room temperature and filtered to remove the bulk of the sodium bromide. The solvent was evaporated and the residue distilled to yield an orange oil (2.00 g, yield: 33%), b.p. 20^0C/0.8 mBar. IR ν_{max} 3105, 2931, 1520, 1472, 1125, 796, 670 cm^{-1}. ^{1}H NMR (d_8-Acetone): δ 1.41 (t, J = 6.9 Hz, 3H, CH_2CH_3), 4.08 (q, J = 6.9 Hz, 2H, CH_2CH_3), 7.67 (s, 1H, Im H). Calcd for $C_5H_6N_2Cl_2$: C, 36.4; H, 3.66; N, 16.98; Cl, 42.97. Anal. Found: C, 36.05; H, 3.81; N, 16.55; Cl, 42.47 .

5.1.3 1-Ethyl-2-Methyl-5-Nitroimidazole.

2-Methyl-5-nitroimidazole (5.02 g, 0.73 mol) (from Aldrich) was stirred under reflux in dry acetonitrile (100 ml) until most of the product had dissolved. Sodium ethoxide (2.93 g, 0.04 mol) was then added, which effected complete dissolution of the starting material. 1-Bromoethane (4.70 g, 0.04 mol) was then added dropwise over a period of 1h and the resulting solution was heated to reflux temperature for 1h. The reaction mixture was cooled to room temperature and filtered to remove the bulk of the sodium bromide. The solvent was evaporated to give a light brown oil which crystallised on cooling. The crude solid was treated with 20ml of hot toluene and deactivated charcoal, and recytallised to yield a colourless solid (2.91 g, yield: 48%), m.p. 68-70 ^{0}C. IR ν_{max} 3500, 1509, 1462, 1456, 1402, 1199, 846, 756, 655 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.45 (t, J = 7.4 Hz, 3H, CH_2CH_3), 1.94 (s, 3H, CH_3), 3.96(q, J = 7.4 Hz, 4H, CH_2CH_3) 7.7 (s, 1H, Im H). Calcd for $C_6H_9N_3O_2$: C, 46.45; H, 5.85; N, 27.08. Anal. Found: C, 45.95; H, 5.56; N, 27.11.

5.1.4 4,5-Dicyanoimidazole Sodium Salt

Sodium ethoxide (5.51 g, 0.08 mol) was added to a stirred solution of 4,5-dicyanoimidazole (8.62 g, 0.07 mol) (from Aldrich) in ethanol (50 ml) under a nitrogen atmosphere. A white precipitate was formed and the reaction mixture was heated at reflux for 30min. After cooling to room temperature the reaction mixture was filtered to afford a cream coloured solid which was dried at 110^0C for 24h to yield a colourless fine solid (9.26 g, yield: 91%), mp. 360^0C. ^{1}H NMR (DMSO-d_6): δ 7.33 (s, 1H, Im H).

5.1.5 2-Methyl-5-Nitroimidazole Sodium Salt

2-Methyl-5-nitroimidazole (7.00 g, 0.06 mol) (from Aldrich) was dissolved in 50ml water with stirring and heat. Sodium hydroxide (2.20 g, 0.06 mol), dissolved in the minimum volume of water, was added dropwise to the reaction mixture which was then heated to reflux for 1h. The solution was cooled to room temperature and the water was removed by rotary evaporation to yield a green solid which was dried at 110^0C for 24h (7.90g, yield: 96.4%), m.p. 210^0C (decomp.). ^{1}H NMR (DMSO-d_6): δ 2.26 (s, 3H, CH_3), 7.94 (s, 1H, Im H).

5.2 1-Ferrocenylimidazole Derivatives

5.2.1 Synthesis of Intermediates

1-(Ferrocenylmethyl) Trimethylammonium Iodide[60]

N,N,N',N'-Tetramethyldiaminomethane (43.20 g, 0.42 mol) was added dropwise to a cold mixture of phosphoric acid (43.20 g) and glacial acetic acid (400 ml) under nitrogen. Ferrocene (46.40 g, 0.25 mol) was then added and the solution was stirred at reflux temperature for 6h. After cooling, the solution was poured into water (500 ml) and extracted with diethyl ether (3 x 100 ml) to remove any trace of unreacted ferrocene. The aqueous layer was then made alkaline by slow additions of NaOH (245 g) and extracted with diethyl ether (3 x 100 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to afford dimethylaminoethylferrocene as a dark orange oil. The latter was dissolved in methanol (54 ml) and excess methyl iodide (54 ml) was added slowly. The solution was then stirred at reflux temperaturefor 10 minutes. The product separated as an oil when diethyl ether (800 ml) was added and crystallised on being scratched. The yellow solid (30.50 g, yield: 64%) was then collected by filtration, washed with diethyl ether (2 x 50 ml) and dried at room temperature, m.p. 220-222^0C (decomp.) [lit. m.p. 220^0C (decomp.)], ^{1}H NMR ($CDCl_3$): δ 3.30 (s, 9H, $NCH_2(CH_3)_3$, 4.28 (s, 5H, Cp H), 4.31 (t, J = 1.5 Hz, 2H, Cp H), 4.57 (t, J = 1.5 Hz, 2H, Cp H), 4.88 (s, 2H, Fc-CH_2-).

Imidazole Sodium Salt[10]

A solution of imidazole (7.00 g, 0.10 mol) and NaOH (4.12 g, 0.10 mol) in water (100 ml) was stirred at reflux temperature for 10 minutes. The solution was then cooled and the solvent evaporated to yield a pale yellow solid. The latter was dried at 200^0C to give the imidazole sodium salt as a pale yellow crystalline powder (8.80 g, yield: 95%).

Ferrocenylmethyl Azide[70]

A solution of (ferrocenylmethyl)trimethylammonium iodide (28.45 g, 0.07 mol) and sodium azide (28.10 g, 0.43 mol) in water (300 ml) was stirred under reflux for 6h. The solution was cooled and extracted wih diethyl ether (3 x 100 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to afford ferrocenylmethyl azide as an orange oil which solidified on cooling to give an orange solid (10.67 g, yield: 60%), m.p. 32-33^0C [lit. m.p. 32-34^0C], ^{1}H NMR ($CDCl_3$): δ 4.11 (s, 2H, Fc-CH_2-), 4.16 (s, 5H, Cp H), 4.19 (t, J = 1.5 Hz, 2H, Cp H), 4.22 (t, J = 1.5 Hz, 2H, Cp H).

1-Ferrocenylmethylamine .

Method A:[71] A solution of ferrocenylmethyl azide (13.11 g, 0.05 mol) and triphenylphosphine (14.40 g, 0.05 mol) in ether (200 ml) was stirred at room temperature for 24 h in a flask exposed to the moist atmosphere. Water (20 drops) was added and stirring continued for 1h. The mixture was then filtered from triphenylphosphine oxide, the filtrate dried over potassium hydroxide and the solvent removed. The residue was dissolved in anhydrous benzene (150 ml) and saturated with hydrogen chloride. Ferrocenylmethylamine hydrochloride separated and was collected by filtration as a yellow solid. This solid was shaken with potassium hydroxide solution (40%) and the liberated amine extracted with diethyl ether (3 x 100 ml). The extracts were dried ($MgSO_4$) and evaporated to afford a dark orange oil which was distilled to give ferrocenylmethylamine as an orange oil (7.60 g, 65%),

b.p. 108-110^{0}C/0.3 mBar [lit. b.p. 108-110^{0}C/0.3 mBar], ^{1}H NMR ($CDCl_3$): δ 1.64 (bs, 2H, N*H*$_2$), 3.54 (s, 2H, Fc-C*H*$_2$-), 4.11-4.17 (m, 9H, Cp H).

Method B: A solution of ferrocenylmethyl azide (10.00 g, 0.04 mol) in anhydrous diethyl ether (100 ml) was added dropwise under nitrogen to a slurry of lithium aluminium hydride (5.00 g, 0.13 mol) in anhydrous diethyl ether (300 ml). The mixture was then stirred at reflux temperature for 2h, cooled and hydrolyzed by careful dropwise addition of water (200 ml). The ether phase was separated and acidified with 10% HCl to precipitate ferrocenylmethylamine hydrochloride which was collected by filtration. This solid was shaken with potassium hydroxide solution (40%) and the liberated amine extracted with diethyl ether (3 x 100 ml). The extracts were dried ($MgSO_4$) and evaporated to afford a dark orange oil which was distilled to give ferrocenylmethylamine as an orange oil, as in Method A (5.00 g, yield: 58%).

5.2.2 1-Ferrocenylmethylimidazole

Method A: A solution of (ferrocenylmethyl)trimethylammonium iodide (5 g, 0.01 mmol), imidazole (0.98 g, 0.01 mol) and potassium carbonate (2.69 g, 0.02 mol) in anhydrous MeCN (100 ml) was heated to reflux temperature for 12hr. The cooled solution was poured into water (100 ml) and extracted with chloroform (3 x 75 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to give an orange oil. 1,1,1-Trichloroethane (50 ml) was added and 1,3-di(ferrocenyl-methyl)imidazolium iodide precipitated as a yellow solid (0.65 g) which was collected by filtration and dried at room temperature. 1,1,1-Trichloroethane was evaporated to afford 1-ferrocenylmethylimidazole as a yellow fine solid (1.74 g, yield: 51%), m.p. 75-77^{0}C. IR ν_{max} 3105, 1497, 1441, 1218, 1094, 1069, 821, 489, 486 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 4.15-4.18 (m, 9H, Cp H), 4.84 (s, 2H, Fc-*C*H$_2$-), 6.89 (s, 1H, 5-Im H), 7.00 (s, 1H, 4-Im H), 7.46 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 46.59 (Fc-*C*H$_2$), 68.40-68.66 (Cp *C*-H and Cp *C*-C), 82.49 (2-Im C), 118.95 (4-Im C), 136.48 (5- Im C). Calcd for $C_{14}H_{14}N_2Fe$: C, 63.18; H, 5.3; N, 20.99. Anal. Found: C, 62.85; H, 5.39; N, 10.25; Fe, 20.81.

Method B: A solution of (ferrocenylmethyl)trimethylammonium iodide (3.00 g, 0.08 mol) and the imidazole sodium salt (0.77 g, 0.09 mol) in anhydrous MeCN (75 ml) was heated to reflux temperature for 12hr. The cooled solution was poured into water (100 ml) and extracted with chloroform (3 x 75 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to give an orange oil which slowly solidified to afford 1-ferrocenylmethylimidazole as a yellow solid (1.43 g, yield: 69%).

Method C: A solution of ferrocenylmethylamine (2.00 g, 0.01 mol) and aqueous ammonia (35%, 0.46 ml, 0.01 mol) in propanol (50 ml) was added to a stirred solution of aqueous glyoxal (40%, 1.17 ml, 0.01 mol) and aqueous formaldehyde (37%, 0.77 ml, 0.01 mol) in propanol (50 ml). The resulting solution was stirred at reflux temperature for 1h. Water (100 ml) was then added and the aqueous solution was extracted with dichloromethane (3 x 50 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to afford an orange oil which slowly solidified to afford 1-ferrocenylmethylimidazole as a yellow solid (2.05 g, yield: 83%).

5.2.3 1-Ferrocenyl 4,5-Dicyanoimidazole

A solution of (ferrocenylmethyl)trimethylammonium iodide (5.00 g, 0.01 mol) and 4,5-dicyanoimidazole sodium salt (1.03 g, 0.01 mol) in anhydrous MeCN (100 ml) was heated at reflux temperature for 48hrs. The cooled solution was poured into water (100 ml) and extracted with chloroform (3 x 75 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to give an orange oil which slowly solidified after addition of diethyl ether and few drops of methanol. Filtration of the solution gave an orange solid which was washed twice with cold methanol to yield orange crystals (3.02g, yield: 74%), m.p. 116-118^{0}C. IR ν_{max} 3093, 2223, 1485, 1441, 1324, 1020, 831, 641, 493cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 4.20 (s, 5H, Cp H), 4.26 (t, J = 1.5 Hz, 2H, Cp H), 4.30 (t, J = 1.5 Hz, 2H, Cp H), 5.02 (s, 2H, Fc-CH_2-), 7.55 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 47.69 (Fc-CH_2-), 68.64-69.49 (Cp *C*-H and Cp *C*-C), 78.17 (2-Im C), 107.72 (*C*N), 111.14 (*C*N), 122.51 (4-Im *C*-CN), 139.95 (5-Im *C*-CN). Calcd for $C_{16}H_{12}N_4Fe$: C, 60.79; H, 3.83; N, 17.72. Anal. Found: C, 60.55; H, 3.84; N, 17.55

5.2.4 1-Ferrocenyl-2-Methyl-5-Nitroimidazole

A solution of (ferrocenylmethyl)trimethylammonium iodide (3.85 g, 0.01mol) and 2-methyl-5-nitroimidazole sodium salt (1.58 g, 0.01 mol) in anhydrous MeCN (100 ml) was heated at reflux temperature for 2 days. The cooled solution was poured into water (100 ml) and extracted with chloroform (3 x 75 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to give an orange oil which slowly solidified after addition of diethyl ether and few drops of methanol. Filtration of the solution gave an orange solid which was recrystallised from methanol to yield orange crystals (3.15 g, yield: 96.6%), mp. 162-164^{0}C. IR ν_{max} 3093, 1534, 1485, 1440, 1388, 1317, 1125, 505, 499 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 2.46 (s, 3H, CH_3), 4.21-4.23 (m, 7H, Cp H), 4.27 (t, J = 2.0 Hz, 2H, Cp H), 4.81 (s, 2H, Fc-CH_2-). ^{13}C NMR ($CDCl_3$): δ 13.33 (CH_3), 47.08 (Fc-CH_2-), 68.87-69.51 (Cp C-H and Cp C-C), 79.88 (2-Im C), 119.24 (5-Im C), 143.97 (C-NO_2). Calcd for $C_{15}H_{15}N_3O_2Fe$: C, 55.41; H, 4.65; N, 12.92. Anal. Found: C, 55.32; H, 4.65; N, 12.75

5.2.5 1-Ferrocenyl-4,5-Dichloroimidazole

A solution of (ferrocenylmethyl)trimethylammonium iodide (5.00 g, 0.01 mol) and 4,5-dichloroimidazole (1.88 g, 0.01 mol) (from Aldrich) in anhydrous MeCN (100 ml) was refluxed for 2 days. The cooled solution was poured into water (100 ml) and extracted with chloroform (3 x 75 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to give an orange oil which slowly solidified after addition of diethyl ether and few drops of methanol. Filtration of the solution gave an orange solid which was washed twice with diethyl ether to yield orange crystals (3.60 g, yield: 83%), m.p. 90-92^{0}C. IR ν_{max} 3093, 1490, 1438, 1334, 1010, 778, 493cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 3.73 (s, 5H, Cp H), 4.22 (t, J = 2.0 Hz, 2H, Cp H), 4.26 (t, J = 2.0 Hz, 2H, Cp H), 4.81 (s, 2H, Fc-CH_2-), 7.28 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 46.41 (Fc-CH_2-), 69.28-69.55 (Cp C-H and C-C), 80.95 (2-Im

C), 126.29 (4-Im *C*-Cl), 134.08 (5-Im *C*-Cl). Calcd for $C_{14}H_{12}N_2Cl_2Fe$: C, 50.19; H, 3.61; N, 8.36; Cl, 21.16. Anal. Found: C, 50.36; H, 3.66, N, 8.17, Cl, 21.39.

5.3 Ferrocenylimidazolium Salts

5.3.1 1-Ferrocenylmethyl-3-Alkylimidazolium Iodides.

A solution of (ferrocenylmethyl)trimethylammonium iodide (5.00 g, 0.01 mol) and the appropriate 1-alkylimidazole (0.01 mol) in anhydrous MeCN (100 ml) was heated at reflux temperature for 12hr. The cooled solution was poured into water (75 ml) and extracted with chloroform (3 x 50 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to give an orange oil. Diethyl ether (50 ml) was then added and the desired salts precipitated on scratching. The yellow solid was collected by filtration, washed with diethyl ether and dried at room temperature.

The following compounds were prepared in the above manner.

1-Ferrocenylmethyl-3-Methylimidazolium Iodide (2.89g, yield: 71%) from 1-methylimidazole, m.p. 146-148^{0}C. IR ν_{max} 3123, 2975, 1560, 1319, 1097, 831, 756, 503, 497 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 4.02 (s, 3H, C*H*$_3$), 4.23 (s, 7H, Cp H), 4.49 (s, 2H, Cp H), 5.36 (s, 2H, Fc-C*H*$_2$-), 7.41 (s, 1H, 5-Im H), 7.47 (s, 1H, 4-Im H), 9.72 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 36.57 (N*C*H$_3$), 49.34 (Fc-*C*H$_2$-), 69.09-69.28 (Cp *C*-H and Cp *C*-C), 121.27 (4-Im C), 123.0 (5-Im C), 135.11 (2-Im C).

1-Ferrocenylmethyl-3-Ethylimidazolium Iodide (2.83g, yield: 67%) from 1-methylimidazole, m.p. 60-62^{0}C. IR ν_{max} 3043, 1553, 1441, 1237, 1156, 1106, 505, 480cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.57 (t, *J* = 7.4 Hz, 3H, CH$_2$C*H*$_3$), 4.25 (s, 7H, Cp H), 4.34 (q, *J* = 7.4 Hz, 2H, C*H*$_2$-CH$_3$), 4.48 (t, *J* = 1.5 Hz, 2H, Cp H), 5.38 (s, 2H, Fc-C*H*$_2$-), 7.28 (s, 1H, 5-Im H), 7.34 (s, 1H, 4-Im H), 9.94 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 15.18 (NCH$_2$*C*H$_3$), 44.85 (N*C*H$_2$CH$_3$), 49.92 (Fc-*C*H$_2$-), 68.68-71.81 (Cp *C*-H and Cp *C*-C), 121.31 (4-Im C), 121.35 (5-Im C), 134.44 (2-Im C).

1-Ferrocenylmethyl-3-Propylimidazolium Iodide (2.96g, yield: 68%) from 1-propylimidazole, m.p. 102-104^{0}C. IR ν_{max} 3079, 1558, 1444, 1237, 1150, 500, 479 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 0.98 (t, *J* = 7.4 Hz, 3H, $CH_2CH_2CH_3$), 1.95 (m, 2H, $CH_2CH_2CH_3$), 4.24-4.27 (m, 9H, Cp H and $CH_2CH_2CH_3$), 4.49 (t, *J* = 1.5 Hz, 2H, Cp H), 5.41 (s, 2H, Fc-CH_2-), 7.28-7.29 (m, 2H, 4-Im H and 5-Im H), 10.08 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 10.29 ($NCH_2CH_2CH_3$), 23.06 ($NCH_2CH_2CH_3$), 49.23 ($NCH_2CH_2CH_3$), 51.15 (Fc-CH_2-), 68.66-71.80 (Cp *C*-H and Cp *C*-C), 121.32 (4-Im C), 121.71 (5-Im C), 134.59 (2-Im C).

1-Ferrocenylmethyl-2-Methyl 3-Ethyl 5-Chloroimidazolium Iodide (3.90g, yield: 83%) from 1-ethyl-2-methyl-5-chlorolimidazole (from Aldrich), m.p. 150^{0}C (decomp). IR ν_{max} 2978, 1526, 1410, 1258, 1184, 1105, 750, 507, 495 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.47 (t, J = 7 4 Hz, 3H, CH_2CH_3), 3.03 (s, 3H, CH_3), 4.23 (q, *J* = 7.4 Hz, 2H, CH_2CH_3), 4.29 (t, *J* = 1.5 Hz, 2H, Cp H), 4.31 (s, 5H, Cp H), 4.45 (t, *J* = 1.5 Hz, 2H, Cp H), 5.37 (s, 2H, Fc-CH_2-), 7.20 (s, 1H, 4-Im H). ^{13}C NMR ($CDCl_3$): δ 12.72 (NCH_2CH_3), 14.70 (CH_3), 41.78 (NCH_2CH_3), 49.28 (Fc-CH_2-), 68.88-71.76 (Cp *C*-H and Cp *C*-C), 117.41 (C-Cl), 123.11 (5-Im C), (2-Im C).

1-Ferrocenylmethyl-3-Butylimidazolium Iodide (3.64g, yield: 82%) from 1-butylimidazole (from Aldrich), as an orange oil. IR ν_{max} 3072, 1558, 1463, 1237, 1151, 1105, 512, 499 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 0.88 (t, *J* = 7.4 Hz, 3H, $CH_2CH_2CH_2CH_3$), 1.27 (m, 2H, $CH_2CH_2CH_2CH_3$), 1.80 (m, 2H, $CH_2CH_2CH_2CH_3$), 4.18-4.22 (m, 9H, Cp H and $CH_2CH_2CH_2CH_3$), 4.45 (t, *J* = 1.5 Hz, 2H, Cp H), 5.33 (s, 2H, Fc-CH_2-), 7.35 (s, 2H, 4-Im H and 5-Im H), 9.86 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 12.97 ($NCH_2CH_2CH_2CH_3$), 18.81 ($NCH_2CH_2CH_2CH_3$), 31.48 ($NCH_2CH_2CH_2CH_3$), 46.59 ($NCH_2CH_2CH_2CH_3$), 49.03 (Fc-CH_2-), 68.62-71.77 (Cp *C*-H and Cp *C*-C), 121.34 (4-Im C), 121.64 (5-Im C), 134.51 (2-Im C).

5.3.2 1,3-Di(Ferrocenylmethyl) Imidazolium Iodide.

Method A: A solution of (ferrocenylmethyl)trimethylammonium iodide (5.00 g, 0.01 mol), imidazole (0.45 g, 0.01 mol) and potassium carbonate (1.35 g, 0.01 mol) in anhydrous MeCN (100 ml) was heated to reflux temperature for one week. The cooled solution was poured into water (100 ml) and extracted with chloroform (3 x 75 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to give an orange oil. 1,1,1-Trichloroethane

(50 ml) was added and 1,3-di(ferrocenylmethyl)imidazolium iodide precipitated as a yellow solid (2.6 g, yield: 68%) which was collected by filtration and dried at room temperature, m.p. 170^{0}C (decomp.). IR ν_{max} 3066, 2938, 1550, 1142, 1100, 826, 514, 498 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 4.22 (s, 14H, Cp H), 4.44 (s, 4H, Cp H), 5.31 (s, 4H, Fc-C*H*$_2$-), 7.17 (s, 2H, 4-Im H and 5-Im H), 9.92 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 49.85 (Fc-*C*H2-), 68.75-69.66 (Cp *C*-H and Cp *C*-C), 120.82 (Im C), 134.66 (2-Im C). Calcd for $C_{25}H_{25}N_2Fe_2I$: C, 50.71; H, 4.25; N, 4.73; Fe, 18.86; I, 21.43. Anal. Found: C, 50.14; H, 4.24; N, 4.95; Fe, 18.39; I, 21.1. Subsequent evaporation of the remaining 1,1,1-trichloroethane solution yielded 1-ferrocenylimidazole as orange crystals (0.80 g, yield: 23%).

Method B: A solution of (ferrocenylmethyl)trimethylammonium iodide (1.8 g, 4.68 mmol) and 1-ferrocenylmethylimidazole (1.31 g, 0.01 mol) in anhydrous MeCN (50 ml) was refluxed overnight. The cooled solution was poured into water (75 ml) and extracted with chloroform (3 x 50 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to give a sticky solid which was washed with 1,1,1-trichloroethane (20 ml) to give 1,3-di(ferrocenylmethyl)imidazolium iodide as a yellow solid (2.21 g, yield: 80%).

5.3.3 General Procedure for the Preparation of Ferrocenylimidazolium Hexafluorophosphates

Ammonium hexafluorophosphate (0.01 mol) was added in one portion to a solution of the appropriate ferrocenylimidazolium iodide (0.01 mol) in acetone (100 ml) and the reaction mixture was stirred at room temperature for 24h. The solution was poured into water (150 ml) and the aqueous phase was extracted with dichloromethane (3 x 50 ml). The extracts were washed with water (2 x 50 ml), dried ($MgSO_4$) and evaporated to yield the ferrocenylimidazolium hexafluorophosphate as orange crystals.

The following compounds were prepared in the above manner.

1-Ferrocenylmethyl-3-Methylimidazolium Hexafluorophosphate (3.71g, yield: 87%), m.p. 134-135^{0}C. IR ν_{max} 3167, 3105, 2964, 1565, 1150, 1100, 834, 561, 531, 499 cm^{-1}. ^{1}H NMR (d_6-Acetone): δ 4.10 (s, 3H, C*H*$_3$), 4.23 (s, 7H, Cp H), 4.55 (s, 2H, Cp H), 5.38 (s, 2H, Fc-

CH_2-), 7.45 (s, 1H, 5-Im H), 7.50 (s, 1H, 4-Im H), 8.70 (s, 1H, 2-Im H). ^{13}C NMR (d_6-Acetone): δ 37.10 (NCH_3), 50.02 (Fc-CH_2-), 69.22-69.34 (Cp *C*-H and Cp *C*-C), 122.44 (4-Im C), 123.90 (5-Im C), 133.97 (2-Im C). Calcd for $C_{15}H_{17}N_2FePF_6$: C, 42.28; H, 4.02; N, 6.57. Anal. Found: C, 42.08 ; H, 4.08; N, 6.22.

1-Ferrocenylmethyl-3-Ethylimidazolium Hexafluorophosphate (3.97g, yield: 90%), m.p. 119-120^{0}C. IR ν_{max} 3130, 2968, 1564, 1106, 827, 561, 511, 492 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.58 (t, *J* = 7.4 Hz, 3H, CH_2CH_3), 4.25 (s, 7H, Cp H), 4.33 (q, *J* = 7.4 Hz, 2H, CH_2-CH_3), 4.50 (t, *J* = 1.5 Hz, 2H, Cp H), 5.39 (s, 2H, Fc-CH_2-), 7.30 (s, 1H, 5-Im H), 7.35 (s, 1H, 4-Im H), 9.00 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 14.60 (NCH_2CH_3), 44.58 (NCH_2CH_3), 49.33 (Fc-CH_2-), 68.90-69.39 (Cp *C*-H and Cp *C*-C), 121.11 (4-Im C), 121.25 (5-Im C), 133.78 (2-Im C). Calcd for $C_{16}H_{19}N_2FePF_6$: C, 43.66; H, 4.35; N, 6.36. Anal. Found: C, 43.42; H, 4.25; N, 6.17.

1-Ferrocenylmethyl-3-Propylimidazolium Hexafluorophosphate (4.18g, yield: 92%), m.p. 94-95^{0}C. IR ν_{max} 3167, 3105, 2964, 1565, 1150, 1100, 834, 561, 531, 499 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 0.93 (t, *J* = 7.4 Hz, 3H, $CH_2CH_2CH_3$), 1.88 (m, 2H, $CH_2CH_2CH_3$), 4.07 (t, *J* = 7.4 Hz, 2H, $CH_2CH_2CH_3$), 4.24-4.26 (m, 7H, Cp H), 4.40 (t, *J* = 1.5 Hz, 2H, Cp H), 5.18 (s, 2H, Fc-CH_2-), 7.22 (s, 2H, 4-Im H and 5-Im H), 8.51 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 10.06 ($NCH_2CH_2CH_3$), 22.96 ($NCH_2CH_2CH_3$), 49.17 ($NCH_2CH_2CH_3$), 51.24 (Fc-CH_2-), 69.03-69.38 (Cp *C*-H and Cp *C*-C), 121.38 (4-Im C), 121.62 (5-Im C), 133.76 (2-Im C). Calcd for $C_{17}H_{21}N_2FePF_6$: C, 44.96; H, 4.66; N, 6.17. Anal. Found: C, 44.73; H, 4.64; N, 5.99.

1-Ferrocenylmethyl-2-Methyl-3-Ethyl-5-Chloroimidazolium Hexafluorophosphate (4.06g, yield: 83%), m.p. 91-92^{0}C. IR ν_{max} 3130, 2968, 1564, 1106, 827, 561, 511, 492 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.39 (t, J = 7.4 Hz, 3H, CH_2CH_3), 3.00 (s, 3H, CH_3), 4.20 (q, *J* = 7.4 Hz, 2H, CH_2CH_3), 4.25-4.27 (m, 7H, Cp H), 4.38 (t, *J* = 1.5 Hz, 2H, Cp H), 5.10 (s, 2H, Fc-CH_2-), 6.99 (s, 1H, 4-Im H). ^{13}C NMR ($CDCl_3$): δ 9.78 (NCH_2CH_3), 13.72 (CH_3), 41.23 (NCH_2CH_3), 48.57 (Fc-CH_2-), 69.04-71.62 (Cp *C*-H and Cp *C*-C), 116.96 (C-Cl), 122.85 (5-Im C), (2-Im C). Calcd for $C_{17}H_{20}N_2ClFePF_6$: C, 41.79; H, 4.12; N, 5.73; Cl, 7.25. Anal. Found: C, 42.05; H, 4.17; N, 5.86; Cl, 7.13.

1-Ferrocenylmethyl-3-Butylimidazolium Hexafluorophosphate (4.12g, yield: 88%), m.p. 123-124^{0}C. IR ν_{max} 3155, 3094, 2968, 1553, 1150, 840, 555, 504, 480 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 0.89 (t, J = 7.4 Hz, 3H, $CH_2CH_2CH_2CH_3$), 1.32 (m, 2H, $CH_2CH_2CH_2CH_3$), 1.81 (m, 2H, $CH_2CH_2CH_2CH_3$), 4.20-4.25 (m, 9H, Cp H and $CH_2CH_2CH_2CH_3$), 4.50 (t, J = 1.5 Hz, 2H, Cp H), 5.35 (s, 2H, Fc-CH_2-), 7.32 (s, 2H, 4-Im H and 5-Im H), 8.91 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 12.82 ($NCH_2CH_2CH_2CH_3$), 18.61 ($NCH_2CH_2CH_2CH_3$), 30.85 ($NCH_2CH_2CH_2CH_3$), 46.72 ($NCH_2CH_2CH_2CH_3$), 49.23 (Fc-CH_2-), 68.70-71.57 (Cp C-H and Cp C-C), 121.36 (4-Im C), 121.58 (5-Im C), 133.76 (2-Im C). Calcd for $C_{18}H_{23}N_2FePF_6$: C, 46.17; H, 4.95; N, 5.98. Anal. Found: C, 45.91; H, 4.86; N, 5.73.

1,3-Di(Ferrocenylmethyl)imidazolium Hexafluorophosphate (4.23g, yield: 80%), m.p. 150-152^{0}C. IR ν_{max} 3155, 3105, 1559, 1106, 834, 555, 505, 497 cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 4.25 (s, 14H, Cp H), 4.45 (s, 4H, Cp H), 5.29 (s, 4H, Fc-CH_2-), 7.19 (s, 2H, 4-Im H and 5-Im H), 8.94 (s, 1H, 2-Im H). ^{13}C NMR ($CDCl_3$): δ 49.85 (Fc-$CH2$-), 68.75-69.66 (Cp C-H and Cp C-C), 120.82 (Im C), 134.66 (2-Im C). Calcd for $C_{25}H_{25}N_2Fe_2PF_6$: C, 49.21; H, 4.13; N, 4.59. Anal. Found: C, 48.98; H, 4.14; N, 4.78.

5.4 Diels-Alder Reactions with Ferrocenylimidazolium Iodides as Lewis Acids

The appropriate ferrocenylimidazolium salt (0.2 equivalents) was weighed accurately into a 20 ml screw-top vial equipped with a small magnetic stirrer. Then 20ml of dry dichloromethane was added and the reaction vessel placed on a cryostatically controlled cold plate at –35^{0}C. The catalyst was stirred for 10 minutes to dissolve and then freshly cracked cyclopentadiene (5 equivalents) was added using a micropipette. The reaction mixture was then stirred for another 15 minutes. Methacrolein (1.0 mole equivalent) was added using a micropipette and the reaction mixture stirred at –35^{0}C for 48h. The excess dichloromethane was evaporated carefully at room temperature and the resulting residue was eluted on silica gel using 50%v/v petroleum ether 60/80 in dichloromethane as solvent to afford pure fractions of the Diels-Alder adduct. The solvent was once again carefully removed from the collected fractions at room temperature to yield the pure adduct as a colourless oil. Adduct yields were determined by use of a SARTORIOUS BP 121 S analytical balance, and the endo:exo ratios for each adduct were determined using a Bruker AVANCE Series 400 Mhz spectrometer.

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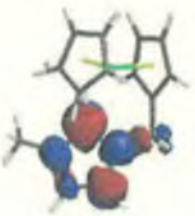
APPENDICES

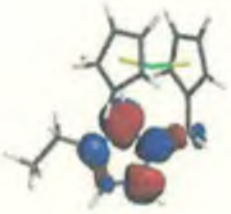
APPENDIX A

Molecular models of the Ferrocenylimidazolium iodide salts.



1-Methyl (99)-Top view

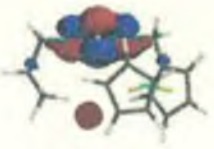
1-Methyl (99)-Side view



1-Ethyl (100)-Top view

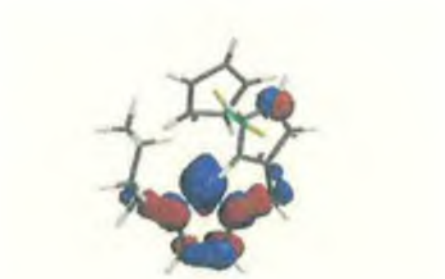
1-Ethyl (100)-Side view

1-Propyl (101)-Top view



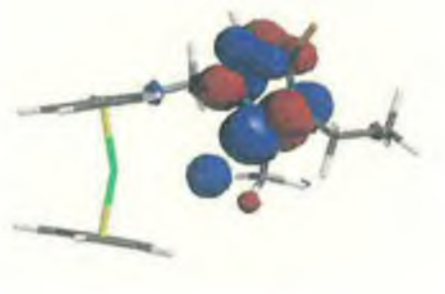
1-Propyl (101)-Side view

APPENDIX A (cont'd.)

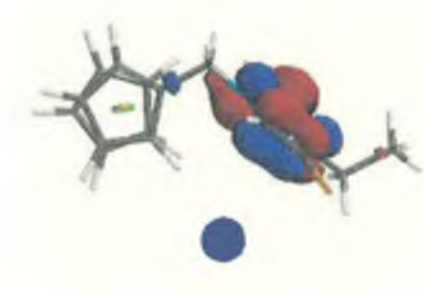


1-Butyl (102)-Top view

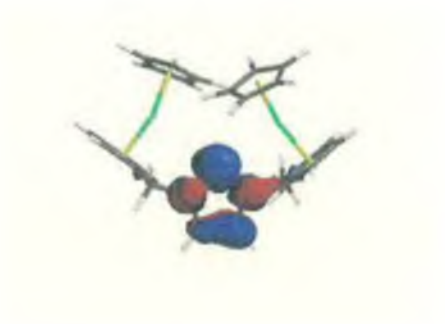
1-Butyl (102)-Side view



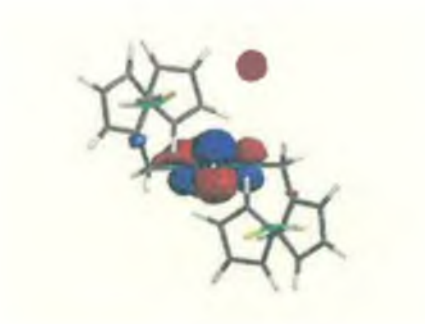
2-Chloro-3-ethyl-5-methyl (109)-Top view



2-Chloro-3-ethyl-5-methyl (109)-Side view



1,3-diFerrocenyl (110)-Top view



1,3-diFerrocenyl (110)- Side view