## THE SYNTHESIS AND ANION COORDINATION CHEMISTRY OF NOVEL MONO- AND BIFUNCTIONAL BORYLMETALLOCENES

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### Abstract

The synthesis, characterisation and anion binding properties of a series of bifunctional boryl-substituted ferrocene systems, and monofunctional borylsubstituted ferrocene and cymantrene systems are reported. Thus, the bis-borylated ferrocene systems:  $Fe[\eta^5-C_5H_4B(OR)_2]_2$  and  $Fe[\eta^5-C_5H_4Bcat]_2$  [where  $(OR)_2 =$ OCH(Ph)CH(Ph)O (1a) or OCH<sub>2</sub>CH(2-napthyl)O (5a), and cat = catecholate (2a), 3,5-di-tert-butylcatecholate (3a), or 3-methoxycatecholate (4a)]; and the monoborylated ferrocenes and cymantrenes  $(\eta^5-C_5H_5)Fe[\eta^5-C_5H_4B(OR)_2]$  (1b),  $[\eta^5 (\eta^5-C_5H_5)Fe[\eta^5-C_5H_4Bcat]$  $C_5H_4B(OR)_2$ ]Mn(CO)<sub>3</sub> (7), (2b), and [η<sup>5</sup>- $C_5H_4B_{cat}M_n(CO)_3$  (8) [where (OR)<sub>2</sub> = OCH(Ph)CH(Ph)O and cat = catecholate] have been synthesised and characterised by NMR, UV/Vis and IR spectroscopy, mass spectrometry, elemental microanalysis, and in most cases by X-ray diffraction. Electrochemical analyses of all ferrocene-based compounds has demonstrated the electronic and redox properties associated with boryl-substituted metallocenes, and allowed a comparison to be made between mono- and disubstituted systems.

The anion binding characteristics of the borylated metallocenes and halfsandwich compounds have been probed by spectroscopic (including NMR, UV/Vis, fluorescence and IR spectroscopy) and electrochemical techniques, revealing a specific affinity for binding of the fluoride ion. Binding is shown to occur through monodentate coordination of fluoride, even for the bifunctional Lewis acids such that two equivalents of the anion are bound by the ferrocenyl-host system. In particular, the bis-borylferrocene receptors display remarkable behaviour on complexation of two equivalents of fluoride, such that a colorimetric response is observed on fluoride binding, attributable to the redox chemistry of the ferrocene moiety to which the binding site is covalently linked.

The synthesis, characterisation and potential hydrogen fluoride binding capabilities of mixed Lewis acidic boron-Lewis basic nitrogen containing systems are also presented here. Both  $(\eta^5-C_5H_5)Fe[\eta^5-C_5H_4B(OCH_2CH_2)NCH_3]$  (9a) and  $(\eta^5-C_5H_5)Fe[\eta^5-C_5H_4B(OR)_2]$  [where  $(OR)_2 = OCH_2CH(CH_2NC_5H_{10})O$ ] (10a) have been synthesised and characterised by standard techniques, and the former shown by X-ray diffraction to display an intramolecular N-B dative bond. In addition to these newly synthesised Lewis acid-Lewis base-containing systems, hydrogen fluoride binding studies involving the literature compound 2-(*N*,*N*-dimethylaminomethyl)ferrocene boronic acid (11a) are also presented. Analyses of the reactions of different hydrogen fluoride sources with these three compounds have been performed *via* NMR spectroscopy, electrochemistry, and in the cases of 9a and 11a, by X-ray crystallography. The results indicate that HF treatment of 9a and 10a, causes B-O bond cleavage leading to loss of the amine function. The Lewis basic component is preserved in the treatment of 10a with HF, however, leading to formation of an HF adduct.

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# Notes

The following abbreviations were used in the text:

Ar = aryl	FT = Fourier Transform
br = broad	h = hours
$^{n}Bu = -CH_{2}CH_{2}CH_{2}CH_{3}$	i = current
$^{\prime}\mathrm{Bu} = -\mathrm{C}(\mathrm{CH}_3)_3$	$^{\prime}\mathrm{Pr}=-\mathrm{CH}(\mathrm{CH}_{3})_{2}$
18-C-6 = 18-crown-6	IR = infrared
calc. = calculated	J = coupling constant
$cat = 1,2-O_2C_6H_4$	$\lambda =$ wavelength
$Cp = cyclopentadienyl, \eta^5 - C_5 H_5$	m = multiplet
CV = cyclic voltammetry	MAO = methylalumoxane
$\delta = NMR$ chemical shift	md = medium
d = doublet, days	$Me = -CH_3$
DCM = dichloromethane	MeCN = acetonitrile
DFT = density functional theory	min. = minutes
DMF = dimethylformamide	MS = mass spectrometry
DMSO = dimethylsulphoxide	v = stretching mode
E = oxidation potential	NMR = nuclear magnetic resonance
EI = electron ionisation	obs. = observed
ES = electrospray	$\mathbf{Ph} = -\mathbf{C_6H_5}$
$Et = -CH_2CH_3$	ppm = parts per million
Fc = ferrocenyl, $(\eta^5 - C_5H_5)Fe(\eta^5 - C_5H_4)$	q = quartet
fc = ferrocenediyl, $(\eta^5 - C_5 H_4)_2$ Fe	Ref. = reference
FcH = ferrocene, $(\eta^5 - C_5 H_5)_2$ Fe	RT = room temperature
$FcH^{+} = ferrocenium, [(\eta^{5}-C_{5}H_{5})_{2}Fe]^{+}$	s = singlet

st = strong

S.C.E = Saturated Calomel Electrode

t = triplet

THF = tetrahydrofuran

 $TMS = -Si(CH_3)_3$ 

UV/Vis = ultraviolet/visible

VT-NMR = variable temperature nuclear magnetic resonance

w = weak

w.r.t. = with respect to

1 Torr = 1 mmHg = 133.3 Pa

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## **Chapter One**

### Introduction

#### 1.1 Introduction

The field of anion recognition has emerged as an area of intense interest over recent decades, forming a significant contribution to the more general domain of supramolecular chemistry. Several definitions exist to describe the field, however, it was the Nobel prize-winner Jean-Marie Lehn, who best described the field as "the chemistry of the intermolecular bond." Thus taking into account the non-covalent interactions that can occur between two molecules, for example, a host species and its associated guest. A major contributor to this area of chemistry includes the recognition of cations, which has been the focus of many research groups over the past forty years or so. For example, early cation receptors which initiated such interest include crown ethers, capable of alkali metal cation complexation (1967),<sup>1</sup> and the appropriately named "proton sponge," reported in 1968 by Alder and coworkers.<sup>2</sup> The analogous complexation of anions, however, has received somewhat less attention, although surprisingly, the first inorganic anion receptor I was developed in 1968, as a macrobicyclic host capable of chloride binding (Figure 1.1).<sup>3</sup> It was not until the late 1970s however, when the area of anion recognition attracted considerable interest, with the work of Lehn and colleagues.<sup>4</sup>



Figure 1.1 A diprotonated 1,11-diazabicyclo[9.9.9]nonacosane system capable of binding chloride, as reported by Park and Simmons.

Several reasons have been advanced to explain why anion binding has been investigated to a lesser extent, all of which reflect the difficulty with which anion recognition is achieved. Firstly, anions possess a lower charge density and are of larger ionic radii compared to their isoelectronic cationic counterparts. Hence, potential receptors must therefore be able to accommodate the relatively larger guest species, and receptor frameworks of considerable size are usually required. Secondly, anions typically display a high free energy of solvation, another factor that must be overcome if specific anions are to be selectively recognised by a host receptor. In addition, the sensitivity of anionic species towards pH, the fact that they are highly solvated, and the vast range of geometries that anions can adopt, all add to the challenge significantly. Despite these drawbacks, several recent books and reviews have been published highlighting the various systems capable of anion and Lewis base sensing.5-12 From the literature material, it appears that anion and molecular recognition can be achieved via somewhat varied approaches. In many cases, binding is brought about by multiple hydrogen bonding interactions between the receptor and its guest, in some cases supplemented by an intrinsic electrostatic interaction with a cationic host.<sup>13-16</sup> Alternative modes of anion/Lewis base binding have been reported to a lesser extent, for example coordination to a Lewis acidic centre which forms part of the binding site.<sup>17-21</sup>

The contents of this chapter aim to summarise the literature reports that are most relevant to the chemistry presented within this thesis; thus a brief description of the various anion binding (particularly fluoride) reports is given, together with a summary of the chemistry concerning borylated metallocene systems.

#### 1.2 Anion recognition

#### 1.2.1 Binding via hydrogen bonding (and electrostatic) interactions

The coordination of anionic guest species by hydrogen bond donating receptors is amply demonstrated in nature itself. Thus, the transport of anions such as sulphate and phosphate across cell membranes is known to occur by formation of a host-guest species, in which a neutral receptor protein binds the anion *via* multiple hydrogen bonding interactions.<sup>22</sup> In these cases, anion complexation is made selective by appropriately positioned hydrogen bond donors which make up the binding site, such that only specific anions can fit into the binding cavity.

The use of hydrogen bonding in the binding of anionic species has been exploited by several research groups, to the extent that a variety of frameworks possessing hydrogen bond donating moieties have been reported in the literature. As mentioned previously, the binding of anionic species by hydrogen bonding is often accompanied by an intrinsic electrostatic interaction if the hydrogen bond donors are in protonated form. One of the earlier examples of this type of host-guest interaction was reported by Graf and Lehn, in which the encapsulation of  $F^-$ ,  $C\Gamma$  and  $Br^-$  was observed by the protonated cryptate II, illustrated in Figure 1.2.<sup>4</sup>



Figure 1.2 A protonated cryptate system capable of binding F<sup>-</sup>, Cl<sup>-</sup> and Br<sup>-</sup>, as reported by Lehn and co-workers in 1976.

Anion complexation by II was found to result from ionic hydrogen bonding, thus making use of both hydrogen bonding interactions and the inherent electrostatic interaction between the protonated nitrogen centres and the included anion. In particular, chloride binding carried out by treatment of the receptor II with excess quantities of methanolic HCl or HNO<sub>3</sub>/[Me<sub>4</sub>N]Cl, resulted in the formation of the *tetra*-protonated chloride cryptate as revealed by the chemical shift patterns seen in the <sup>13</sup>C NMR spectra. Analogous binding was observed for the inclusion of fluoride and bromide under similar conditions, thus indicating that halide binding by these systems is achieved *via* a tetrahedral array of <sup>+</sup>N-H···X<sup>-</sup> hydrogen bonds. This behaviour was confirmed by the X-ray diffraction study of the chloride-cryptate complex, as reported by Metz and co-workers at around the same time.<sup>23</sup>

Later work by the group of Lehn *et. al.*, extended the investigation of anion receptor molecules to include alternative cryptand systems. In particular, those illustrated in Figure 1.3, III and IV, were both shown to bind the fluoride ion as shown by X-ray diffraction data.<sup>14</sup> In addition, the host-guest complexes of III with  $C\Gamma$ ,  $Br^-$  and  $N_3^-$  were also reported.



**Figure 1.3** Protonated cryptate systems reported by Lehn *et. al.*: III for binding F<sup>-</sup>, CF, Br<sup>-</sup> and N<sub>3</sub><sup>-</sup>, and an octaaza-cryptand, IV for selective F<sup>-</sup> coordination.

In the case of compound III, the four anion coordinated crystal structures revealed varying modes of anion coordination. For the chloride and bromide adducts, binding was shown to occur *via* an octahedral array of hydrogen bonds, whereas the  $N_3^-$  anion complex featured two pyramidal arrays of three hydrogen bonds. It was also concluded that the small size of the fluoride ion meant that it could not bind equivalently to the six protons, and as a result only occupied one side of the cavity *via* a tetrahedral array of four  $^+N-H\cdots F^-$  interactions.

Anion binding studies of the octaaza-cryptand receptor IV, displayed somewhat different results with respect to fluoride coordination.<sup>14</sup> This time, treatment of the macrobicyclic cryptand with one equivalent of  $F^-$  (as [Me<sub>4</sub>N]F), and subsequent crystallisation yielded a solid state structure in which the fluoride anion was located inside the molecular cavity of the receptor, which possesses sixprotonated nitrogen centres (excluding bridgehead nitrogens). The fluoride ion in the solid state structure is thus hexacoordinated to the six ammonium sites in a *quasi trigonal prismatic* geometry.

Since the early work by Lehn and co-workers, several other research groups have also exploited the fluoride binding capabilities of macrocyclic polyammonium systems.<sup>24-26</sup> In particular, the group of Smith *et. al.* further investigated the binding properties of the octaazacryptand IV (Fig. 1.3) and reported a series of protonation constants (from potentiometric pH titration data), together with fluoride and chloride binding constants, also obtained from titration experiments.<sup>25</sup> Furthermore, <sup>1</sup>H and <sup>13</sup>C NMR studies by this group indicated significant changes in chemical shift upon fluoride treatment, whereas smaller shifts were observed upon chloride treatment. From detailed examination of the NMR data, it was concluded that the small fluoride ion binds inside the cavity, whereas the relatively larger chloride ion does not (a fact

presumably reflected in the different binding constants observed for the two halides). The greater selectivity of the system for fluoride was therefore attributed to the ideal size match of the ion for the cryptand cavity.

More recently, <sup>19</sup>F NMR spectroscopy and X-ray crystallography were used to characterise the fluoride binding by an alternative aza cryptand [Figure 1.4, V].<sup>26</sup> Thus, analysis of the <sup>19</sup>F NMR spectra over a range of pH values indicated varying chemical behaviour, with protonated fluoride species (*e.g.* HF) interacting with the protonated form of the cryptand V at low pH, and the fluoride-cryptate being formed at pHs as high as 7.5. Higher pH values (>7.5) resulted in <sup>19</sup>F NMR spectra characteristic of solvated fluoride species in the absence of the macrocycle.



Figure 1.4 Fluoride binding by an alternative aza cryptand, published by Bowman-James and colleagues, 2000.

The existence of the fluoride cryptate was also crystallographically proven, with the fluoride ion clearly adopting a position to one side of the cavity, held by three  $^{+}N-H^{--}F^{-}$  hydrogen bonds. However, co-inhabited with the fluoride ion was a single water molecule, such that this was the first report of a simple Schiff base-derived receptor with two different guest species included.

Alternative methods of anion complexation, particularly fluoride complexation have been demonstrated by the work of Sessler *et. al.*, in the synthesis of a series of porphyrin-related pentaazamacrocycles,<sup>27-29</sup> one example of which is illustrated in Figure 1.5 (VI).<sup>28</sup> In this particular case, solid state structural evidence of fluoride binding to the diprotonated form of sapphyrin VI was obtained as a mixed fluoridehexafluorophosphate salt. The cationic fragment featuring the bound  $F^-$  ion featured a total of five N-H…F<sup>-</sup> interactions, two of which were presumably dominated by the cationic nature of the protonated nitrogen centres.



Figure 1.5 Diprotonated sapphyrin VI, and dipyrrolylquinoxalines VII as selective fluoride receptors as reported by Sessler and co-workers.

Solution phase studies based on VI were reported later, and included calculation of the fluoride binding constant from titrimetric studies monitored by fluorescence or UV absorption spectroscopy in methanol solution. The binding constants ( $K_{\rm S} \sim 1 \times 10^5 \text{ M}^{-1}$ ) indicated a significant interaction for fluoride, which was not the case for chloride or bromide ( $K_{\rm S} < 10^2 \text{ M}^{-1}$ ). Furthermore, cyclic voltammetry

experiments involving fluoride treatment of the receptor indicated both oxidation and reduction waves which were shifted to more negative potentials compared with the analogous chloride and bromide salts of the diprotonated sapphyrin receptor. This was again reported to be characteristic of  $F^-$  coordination.

Later investigations by Sessler *et. al.* have concentrated on somewhat more synthetically accessible systems in the form of dipyrrolylquinoxalines (Figure 1.5, VII).<sup>30</sup> Colorimetric anion sensors for F<sup>-</sup>, Cl<sup>-</sup> or H<sub>2</sub>PO<sub>4</sub><sup>-</sup> utilising such a pyrrolic system with a built-in chromophore were targeted. The anion binding properties of the two derivatives of VII were also compared with the precursor species (2,3dipyrrol-2'-ylethanedione), and a control system in which one of the pyrrole nitrogens was protected with a SEM group (SEM = monotrimethylsilylethoxymethyl). Both UV/Vis and fluorescence spectroscopy were used to monitor the process of anion binding, providing anion complexation constants for which fluoride binding was predominant. In addition, the –NO<sub>2</sub> substituted system VII was found to undertake a dramatic yellow to purple colour change on F<sup>-</sup> addition in DCM and DMSO solution, thus allowing detection of fluoride on a visual level as well as by fluorescence quenching.

Further work by Sessler, has led to the development of further pyrrole-type anion receptors in the form of calix[4]pyrroles VIII, illustrated in Figure 1.6. Initial investigations centred around calixpyrrole frameworks possessing redox active ferrocene moieties, with the aim of electrochemically detecting anion binding *via* changes in the ferrocene/ferrocenium redox couple.<sup>31</sup> However, the electrochemical results upon anion treatment of the receptors appeared unpredictable and difficult to rationalise, hence further work concentrated on the calix[4]pyrrole moiety VIII possessing a fluorescent anthracene reporter function.<sup>32</sup>



Figure 1.6 Calix[4]pyrroles: VIII Fluorescent chemosensors for  $F^-$ ,  $CI^-$  and  $H_2PO_4^-$ ; and IX, a receptor for selective  $F^-$  binding.

In the case of the anthracene-containing calixpyrroles (VIII), addition of anionic species (F<sup>-</sup>, Cl<sup>-</sup>, Br<sup>-</sup> and H<sub>2</sub>PO<sub>4</sub><sup>-</sup>) to a solution of the receptor in either dichloromethane or acetonitrile resulted in fluorescence quenching, enabling stability constants for the formation of the anionic adducts to be determined, from which fluoride was determined to be the most strongly bound. In an attempt to develop a colorimetric anion sensor, the calix[4]pyrrole unit VIII, R = H, was again used to form an anion sensor in which the intensely yellow coloured 4-nitrophenolate anion was present as a guest species.<sup>33</sup> When bound by the calixpyrrole, the yellow colour of the 4-nitrophenolate anion is somewhat subdued, however, upon addition of an alternative anion, particularly fluoride, the bound 4-nitrophenolate is displaced by the added anion (a process followed by <sup>1</sup>H NMR titration studies), to the extent that the intense yellow colour (of free 4-nitrophenolate) returns, as monitored by UV/Vis spectroscopy.

The discovery that calix[4]pyrroles, such as those shown by Fig. 1.6 (VIII) bind anions effectively, has led to a series of modified calix[4]pyrroles with extended cavities.<sup>34</sup> Camiolo and Gale further modified the common framework to include longer and bulkier functional groups, in order to generate "super-extended cavities;" examples are shown in Figure 1.6 (IX).<sup>35</sup> The resulting macrocycles showed high selectivity in anion coordination towards fluoride, evident from the <sup>1</sup>H NMR chemical shift changes and calculated binding constants. Analogous binding of CI<sup>-</sup>, Br<sup>-</sup>, I<sup>-</sup>, H<sub>2</sub>PO<sub>4</sub><sup>-</sup> and HSO<sub>4</sub><sup>-</sup> was shown to be very weak by NMR experiments, thus showing the newly synthesised systems to be fluoride specific.

An alternative system in which fluoride is predominantly bound was developed by Beer and colleagues, incorporating two calix[4]arene fragments linked *via* covalent amide bonds to form compound **X**, Figure 1.7.<sup>36</sup> The hydrogen bond donating amide functions encourage binding within the cavity, which is too small for encapsulation of  $H_2PO_4^-$  or  $HSO_4^-$ , but allows entrance of Cl<sup>-</sup> and F<sup>-</sup>.

Figure 1.7 A bis-calix[4]arene receptor X for the inclusion of fluoride and chloride, as reported by Beer and co-workers in 1995.



<sup>1</sup>H NMR titration experiments with the above anions revealed the formation of host-guest species with X in 1:1 stoichiometry, and allowed stability constant values to be determined. From these calculated values, it was apparent that the receptor X possessed nearly an order of magnitude greater selectivity for fluoride over chloride, with the larger  $HSO_4^-$  and  $H_2PO_4^-$  anions forming much weaker complexes. These observations were attributed simply to anion size, since fluoride and chloride were able to bind more strongly within the receptor cavity.

Macrocyclic anion hosts have also been reported by Farnham, Dixon and coworkers, using a somewhat different approach. The synthesis of a novel fluorinated macrocyclic ether (XI) was carried out and its fluoride binding properties investigated (Scheme 1.1).<sup>37</sup>



Scheme 1.1 A fluorinated macrocyclic ether as a fluoride ion host, Farnham et. al., 1990.

The study included solid state structural characterisation of both the anion free macrocycle **XI**, and its host-guest complex with fluoride **XII**, which revealed substantial conformational change of the 18-membered ring upon fluoride accommodation. Further binding studies involved monitoring the anion binding process by NMR methods (which showed the central fluoride ion to be tightly bound), and *ab-initio* theoretical calculations which indicated a minimum-energy geometry similar to that seen in the crystal structure.

Hossain and Ichikawa, have also examined the specific binding of fluoride, reporting an interesting novel macrotricyclic receptor XIII, possessing an ammonium based binding site.<sup>38</sup> In contrast to the systems described so far, this particular receptor utilised solely electrostatic interactions to effect anion inclusion, with selectivity being governed strictly by the size of the cavity (Figure 1.8).

Figure 1.8 A macrotricyclic receptor for the electrostatic binding of fluoride. H<sub>3</sub>C<sub> $H_3$ C<sub> $H_3$ C<sub> $H_3$ C<sub> $H_3</sub>C<sub><math>H_3$ C<sub> $H_3$ C<sub> $H_3</sub>C<sub><math>H_3$ C<sub> $H_3$ C<sub> $H_3</sub>C<sub><math>H_3$ C<sub> $H_3$ C<sub> $H_3</sub>C<sub><math>H_3$ C<sub> $H_3$ </sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub></sub>

Previous reports of halide inclusion by larger receptors featuring quaternary ammonium ions<sup>39</sup> encouraged the group to attempt fluoride recognition by the smaller analogue **XIII**. The ability of the tetra-ammonium macrotricyclic host to bind fluoride in aqueous solution was therefore tested by convenient <sup>19</sup>F NMR spectroscopy, which led to assignment of the fluoride captured species (an upfield resonance from free solvated F<sup>-</sup>), and determination of a stability constant for the host-guest species ( $K \sim 1.5 \times 10^4$  M<sup>-1</sup> in H<sub>2</sub>O at 298 K).

### 1.2.2 Alternative anion receptor frameworks

Although many other anion receptor species exist that bind exclusively through hydrogen bonding,<sup>40</sup> some alternative anion receptor molecules incorporating a variety of frameworks are also worthy of mention.

MCH3

XIII

One particular framework that has been relatively intensely studied includes the guanidinium group. The role of guanidinium moieties in enzymes serve to effect binding of anionic substrates, and stabilise tertiary protein structures *via* intramolecular salt bridges with carboxylate functions. It is no surprise, therefore that the binding property of the guanidinium group towards oxo-anionic species has been exploited by several research groups.<sup>41</sup> One of the earlier examples of a macrocyclic guanidinium based receptor was presented by the group of Lehn, in which two such functions were built into the receptor **XIV**, Figure 1.9.<sup>42</sup>



Figure 1.9 XIV A macrocyclic guanidinium-based receptor by Lehn *et. al.*; XV binding of oxoanionic species in a bicyclic guanidinium system.

With respect to phosphate and carboxylate binding, Lehn found that these species bind only weakly to the macrocyclic receptor in comparison to analogous polyammonium species. It was concluded that the flexible nature of the receptor, together with the effect of charge delocalisation in the resultant host-guest complex was responsible for the weak binding observed.

A major advance in binding efficacy was provided by Schmidtchen and coworkers, who developed chelating bicyclic guanidinium species such as XV, depicted in Figure 1.9.<sup>43</sup> The result of the bicyclic guest architecture was a reduction in the flexibility of the receptor and improved predictability of the host-guest interaction due to preorganisation for bidentate oxo-anion binding. For example, the binding of *para*-nitrobenzoate by the receptor **XV** was calculated to be relatively strong ( $K = 1.4 \times 10^5$  M<sup>-1</sup> in CDCl<sub>3</sub>) in comparison to macrocyclic systems possessing multiple guanidinium units. Many other groups have since developed similar receptors capable of the binding of carboxylate and related anionic/neutral systems by hydrogen bond donors.<sup>44</sup>

Bondy, Gale and Loeb have recently investigated the recognition of oxoanions by an alternative hydrogen bond donating receptor. In this particular example, the receptor consisted of a platinum(II) nicotinamide complex (Figure 1.10, **XVI**).<sup>45</sup>





It was thought that the amide hydrogen bond donors within the ligand could orientate themselves to bring about successful coordination of anionic species. The parent receptor XVI, synthesised as the di-hexafluorophosphate salt, was characterised crystallographically, displaying the  $PF_6^-$  counterions above and below the metal centre interacting electrostatically, and two molecules of dichloromethane

within the structure hydrogen bonded to the amide C=O groups. Thus, the amide N-H hydrogen bond donating functions were still available for oxo-anion coordination. <sup>1</sup>H NMR titration experiments with  $CF_3SO_3^-$ ,  $ReO_4^-$ ,  $NO_3^-$ ,  $HSO_4^-$ ,  $H_2PO_4^-$  and  $CH_3CO_2^-$  showed the transition metal based receptor to be an effective host for the inclusion of these oxo-anions.

The generation of a range of anion receptor systems featuring organometallic metallocene moieties has been reported by Beer *et. al.*<sup>13</sup> With the aim of targeting specific anionic guest species, a series of ferrocene and cobaltocenium-based receptors (such as those depicted in Figure 1.11) have been synthesised, and their anion binding capabilities evaluated (with anions such as  $HSO_4^-$ ,  $H_2PO_4^-$  and  $CI^-$ ).



Figure 1.11 Charged and neutral organometallic metallocene receptor systems, developed by Beer et. al.

The presence of the redox-active metallocene units enabled monitoring of the anion binding process *via* cyclic voltammetry (CV), which commonly displayed a cathodic shift of the metallocene oxidation potential upon anion complexation. In addition to CV, <sup>1</sup>H NMR titration techniques allowed further evaluation of the

binding process and determination of stability constants for the respective host-guest species including anions such as halide ions and oxo-anions (*e.g.*  $H_2PO_4^-$ ). In the cases of chloride and bromide recognition, structural characterisation further confirmed the results obtained. Larger systems which have subsequently been synthesised and tested include bis-ruthenium(II) bipyridyl macrocycles, and ruthenium(II) bipyridyl-metallocene macrocyclic receptors, most of which demonstrated hydrogen bond anion coordination ability from electrochemical experiments.

#### 1.2.3 Lewis acid based recognition

In addition to receptors capable of anion and Lewis base sensing by hydrogen bond and/or electrostatic interactions, the development of receptors featuring Lewis acidic functional groups has been shown to provide an alternative pathway by which both anion and Lewis base recognition can be achieved. As evidenced by the literature output, this area of supramolecular chemistry has been the subject of much less research effort (in comparison to hydrogen bond donor based systems), with the majority of systems exploiting the Lewis acidic property of boron in a three coordinate environment. The fact that a three-coordinate boryl species in trigonal geometry possesses only six electrons in its outer shell makes it an effective Lewis acid, such that a pair of electrons from an anion or Lewis base can be donated into the remaining empty p<sub>2</sub>-orbital to complete its octet. This kind of Lewis acid host was first exploited by Shriver and Biallas in 1967, whom investigated F<sub>2</sub>BCH<sub>2</sub>CH<sub>2</sub>BF<sub>2</sub>. This compound was shown to act as a chelating host for methoxide.<sup>46</sup> Since then a range of alternative systems have been developed for anion sensing, utilising Lewis acidic aluminium, tin and mercury based systems for example, as well as boron. Within the scope of this investigation, previously reported examples that are most relevant to the chemistry described in this thesis are discussed in Chapter Four, section 4.1, highlighting the ability of boron-based systems to specifically recognise the fluoride anion. Further literature examples of alternative anion/Lewis base binding by Lewis acidic receptors are therefore presented at this point, with the aim of emphasising the potential of these systems to carry out anion/Lewis base recognition.

#### 1.2.3.1 Anion binding by boron-based Lewis acids

Following the initial reports of Shriver and Biallas, it was not until 1985 when Katz investigated oligoboranes as candidates for electron-deficient hosts, which could engage in multidentate complexation with guest anions. The first example reported, involved the synthesis and hydride-abstracting ability of 1,8-napthalenediylbis(dimethylborane) **XVII**, more commonly known as "hydride sponge" (Figure 1.12).<sup>47</sup>



XVII



This bifunctional Lewis acid was found to abstract hydride from a number of sources, including triphenylborohydride and dimethyl-1-napthylborohydride. The hydride anion was observed to be strongly chelated to both boron centres with unusual thermodynamic stability. Evidence of this manifested itself from NMR measurements and X-ray diffraction, which showed the hydride anion unsymmetrically bridged between the two boron centres. Subsequent investigations involved subjecting the dimethylborane **XVII** to donors of fluoride and hydroxide, which were also found to bind successfully, as demonstrated by characteristic shifts and coupling patterns in the <sup>1</sup>H, <sup>19</sup>F and <sup>11</sup>B NMR spectra.<sup>48</sup>

Katz's further research into 1,8-napthalenediylbis(borane) compounds involved the variation of the substituents attached to the two boron centres. Thus, subsequent efforts involved the incorporation of chlorine atoms rather than methyl groups into the structure above to form the bis(dichloroborane)napthalene system (Scheme 1.2, XVIII).<sup>49</sup> The main aim of this substitution was to create a stronger chelating Lewis acid, which was of sufficient strength to bind chloride, since attempts to do so with the hydride sponge had previously failed. Thus, chloride binding experiments were performed according to Scheme 1.2.



Scheme 1.2 Multidentate coordination of chloride: the first bis(boron) chloride chelate.

From <sup>11</sup>B NMR studies, it was concluded that both boron atoms became tetrahedral upon chloride treatment to form the chelated adduct **XIX** as portrayed in Scheme 1.2, rather than a rapid interconversion between inequivalent trigonal and tetrahedral borons by chloride "shuttling." Single crystals of the chloride chelate were grown, and X-ray diffraction studies indicated a slightly distorted tetrahedral geometry at both boron centres. This confirmed the first definitive example of Cl<sup>-</sup> bridging between two boron centres.

In a theoretical study, Jacobson and Pizer investigated anion binding by organoboron macrocyclic hosts of the type illustrated by Figure 1.13.<sup>50</sup> Molecular orbital calculations were carried out on these two classes of multidentate boron-containing macrocycles, together with their H<sup>-</sup>, F<sup>-</sup>, Cl<sup>-</sup> and O<sup>2-</sup> complexes.



Figure 1.13 Potential organoboron anion hosts based on macrobicyclic (n = 3-10) and macrotricyclic (n = 2-4) frameworks.

On the basis of calculated standard enthalpies of reaction, the computational results indicated that in the case of the macrobicyclic host, the binding of a particular anion was not strictly governed by cavity size. For example, H<sup>-</sup> was bound to a similar extent by hosts with n = 4-6, F<sup>-</sup> by hosts with n = 5 and 6; Cl<sup>-</sup> by hosts with n = 6 and 8, and O<sup>2-</sup> by hosts with  $n \ge 4$ . The macrotricyclic host, however, in which anions were found to bind to more than two boron atoms, revealed greater anion specificity with H<sup>-</sup> and O<sup>2-</sup> favouring hosts with n = 2, and F<sup>-</sup> and Cl<sup>-</sup> binding predominantly to hosts with n = 3. In all cases, it was concluded that anion coordination occurs with a change from sp<sup>2</sup> to sp<sup>3</sup> hybridization at boron, and

interestingly, that charge transfer from the anion to the host on binding allows anions to fit into cavities that are smaller than their ionic radii.

A more recent theoretical publication by Aldridge and co-workers, also considered anion binding by multidentate boron-based Lewis acids.<sup>51</sup> Density functional theory (DFT) was used to study two model compounds, namely 1,4,7-trifluoro-1,4,7-triboracyclononane **XX** and its fluorinated analogue **XXI**, both of which are shown in Figure 1.14. The binding properties of these macrocycles with a range of anions were evaluated.



Figure 1.14 Model tribora-macrocyclic Lewis acids as anion complexation agents from DFT studies.

These studies revealed a series of parameters defining the macrocyclic complex geometries, along with binding energies for the various anions (H<sup>-</sup>, F<sup>-</sup>, Cl<sup>-</sup>, Br<sup>-</sup>, CH<sub>3</sub><sup>-</sup>) to **XX** and **XXI**. A common observation was that perfluorination of the triboramacrocycle (to form **XXI**) resulted in considerably enhanced binding energies, which were extremely high for the smaller anions (H<sup>-</sup> and F<sup>-</sup>), implying the potential of these systems to bind such anions in bidentate fashion for hydride, and tridentate for fluoride. The weaker binding of chloride and bromide was attributed to a poorer size match of the respective anion for the macrocyclic cavity. For the methyl anion

however, analysis of the calculated boron-methide bond lengths indicated that binding of the anion within the cavity is essentially monodentate in nature. However, even allowing for the non-chelating nature of this interaction, the binding energy for the perfluorinated system **XXI** was the highest reported to date. Hence, in theory, this triboramacrocycle binds  $CH_3^-$  at least as strongly as Lewis acids such as  $B(C_6F_5)_3$ .

An alternative diboron-containing receptor has been reported by Herberich, Fischer and Wiebelhaus, in which the Lewis acidic boron moieties are built onto a metallocene framework.<sup>52</sup> This group thus presented the first account of a novel cationic molecular pincer, based on a bis(boryl)cobaltocenium ion which they found to display significant variation in its interaction with anions. Substitution chemistry at the boron centres allowed the introduction of two bulky diisopropyl groups per boryl centre thereby generating the receptor 1,1'-bis-(diisopropyl)cobaltocene **XXII**, illustrated in Scheme 1.3. Subsequent oxidation of this species with [FeCp<sub>2</sub>]PF<sub>6</sub> resulted in the corresponding structurally characterised cobaltocenium salt. With regards to anion coordination, NMR spectroscopy (<sup>11</sup>B and <sup>1</sup>H) and X-ray diffraction studies confirmed the bidentate coordination of hydroxide as shown in Scheme 1.8, with the product **XXIII** resulting from oxidation of 1,1'-bis(diisopropyl)cobaltocene with Cu(OH)<sub>2</sub>.



Scheme 1.3 Hydroxide binding between two boryl moieties of a diamagnetic cobaltocenium salt.

Conversely, oxidation of the parent receptor XXII with  $C_2Cl_6$ , resulted in the abstraction of chloride, but this time, coordination of the anion was to a single boron atom *via* a single monodentate acid/base interaction. <sup>11</sup>B NMR spectroscopy, however, was indicative of rapid chloride exchange between the two boron centres in solution at 20°C.

#### 1.2.3.2 Neutral Lewis base recognition by boron-based Lewis acids

The ability of boron-based receptor systems to coordinate Lewis bases as well as anionic species is another area of recognition chemistry that has been well documented by several research groups in recent years.

In addition to the reported "hydride sponge" and related derivatives, further studies by Katz have revolved around the synthesis and Lewis base binding abilities of an anthracene based bidentate Lewis acid XIV.<sup>53</sup> The choice of the 1,8-diethynylanthracene precursor was largely due to its inherent rigidity, and ease of introducing Lewis acidic moieties to form a bidentate ligand with a bridging distance of *ca*. 5 Å. Hence it was thought that this system might be useful in the coordination of guests of considerable size, as shown in Scheme 1.4



Scheme 1.4 Bidentate coordination of 5-methylpyrimidine by 1,8-anthracenediethynylbis(catechol boronate).

Due to potential interest in the recognition of 1,3-dibasic compounds, and the fact that molecular models of the bis-boryl receptor with coordinated species such as pyrimidine indicated nearly strain-free bridged complexes, Katz decided to explore the solution binding properties of the receptor with 5-methylpyrimidine. <sup>1</sup>H NMR titration experiments in CD<sub>2</sub>Cl<sub>2</sub> revealed the predominant formation of the 1:1 bridging complex **XV** (Scheme 1.4), with binding constant  $K_1 = 130 \text{ M}^{-1}$ . Further addition of the guest species resulted in formation of a 2:1 complex for which the binding constant was significantly smaller ( $K_2 = 40 \text{ M}^{-1}$ ). For comparison, similar experiments were carried out with thiazole (one basic atom) and 4-methylpyrimidine (one sterically hindered basic nitrogen), both of which displayed no indication of a bridging interaction with the host from <sup>1</sup>H NMR studies. It was therefore concluded that this particular host was the first rigid diboron receptor for dibasic guests.

With the aim of achieving some form of chiral Lewis base recognition, the group of Takaya *et. al.* have reported the synthesis and amine binding properties of two different chiral boron-based Lewis acids **XVI** and **XVII**,<sup>54,55</sup> both of which are shown pictorially in Figure 1.15.



Figure 1.15 Chiral Lewis acids for the recognition of Lewis basic amines, by Takaya and co-workers.

In the first example (Fig. 1.15, XVI), molecular recognition by the chiral diboronic ester was attempted with benzylamine treatment. The process was followed by <sup>1</sup>H NMR spectroscopy and titration techniques, which involved monitoring of the methine protons of the boronate ester as a function of added amine. From these results, it was apparent that the coordination of two benzylamine molecules occurred, with two different binding constants for the first and second binding process. The resultant values indicated the binding of the second amine molecule was considerably enhanced compared to that of the first molecule ( $K_2 >> K_1$ ), with the overall binding constants were observed for both (R) and (S)-1-phenylethylamine [PhCH(NH<sub>2</sub>)CH<sub>3</sub>] with XVI, such that any degree of chiral recognition was concluded to be minimal.

A second investigation involved probing the selective binding of diamines to the chiral bis-boron receptor **XVII** shown in Figure 1.15. In this case, selective binding was manifested by recognition of the distance between amine groups in 1,2diaminoethane and 1,6-diaminohexane, the latter being shown to be more favourably bound by <sup>1</sup>H NMR spectroscopic studies. This observation was explained by model studies of the respective 1:1 host-guest species, which displayed  $C_2$  symmetric chiral structures with the expected Lewis acid-Lewis base interactions. In addition, the model studies revealed the presence of two hydrogen bonds for the complex with 1,6diaminohexane, which were absent from the smaller amine-Lewis acid complex. A form of chiral discrimination was also observed with experiments involving (*R*,*R*) and (*S*,*S*)-1,2,-diamino-1,2-diphenylethane. <sup>1</sup>H NMR analysis of the binding process in both cases displayed different complexation patterns between the two enantiomers indicating diastereomeric coordination; this particular observation was attributed to involvement of the carbonyl groups of the receptor as Lewis basic sites. Lewis basic amine coordination to multifunctional boron-based receptors has also been investigated by the group of Piers. Two separate reports have highlighted the synthesis and Lewis base coordination chemistry of 2,2'diborabiphenyl based receptor systems, <sup>56,57</sup> as illustrated in Scheme 1.5.

In an initial report, Piers and co-workers presented the synthesis of the silated chlorodiborane compound (XVIII, Scheme 1.5), and its reaction with Lewis bases such as trimethylphosphine and pyridine, resulting in elimination of trimethylsilylchloride and formation of the monodentate 1:2 Lewis acid-Lewis base adducts. For the PMe<sub>3</sub> adduct XXIX, convincing evidence of a phosphorus-boron interaction arose from the crystal structure as well as from spectroscopic techniques.



Scheme 1.5 Lewis acid-base complexes formed with 2,2'-diborabiphenyl receptors.

It was also demonstrated that in addition to simple Lewis bases (such as  $PMe_3$  or  $C_5H_5N$ ), treatment with bifunctional nitrogen bases such as pyridazine or benzo[*c*]cinnoline, generated the 1:1 chelated adduct featuring a  $C_2B_2N_2$  heterocyclic ring.

Further studies exploring the chemistry of the 2:1 trimethylphosphine adduct involved treatment with the aryl-amines as shown in Scheme 1.5, which gave the corresponding monodentate adduct XXX and a chelated adduct XXXI, depending on the stoichiometry in which the reaction was performed. Both bis(amido)-boranes (monodentate bound arylamines, XXX) and the 9,11-diboratacarbazole heterocycles (chelated arylamines, XXXI) were characterised spectroscopically, with X-ray crystallography confirming the existence of the chelated aniline heterocycle.

The use of boryl-based metallocene systems in the binding of guest species has also been exploited by Piers, with two separate reports being recently made concerning the synthesis and Lewis base coordination chemistry of both mono- and bis-borylated ferrocene systems illustrated in Figure 1.16, **XXXII** and **XXXIII** respectively.<sup>58,59</sup> Both systems were synthesised and characterised fully including X-ray diffraction and electrochemical studies. The electron-withdrawing effect of the pentafluorophenyl group acts to increase the Lewis acidity of the boron centres quite significantly, which was thought to be useful in enhancing the anion abstraction properties, thus promoting a stronger binding of anionic species.


Figure 1.16 Mono- and bis-(bis-pentafluorophenylboryl)ferrocenes, capable of binding PMe<sub>3</sub>, Piers *et. al.*, 2001.

In the case of the mono-borylated system **XXXII**, solution spectroscopic and solid state 'structural data suggested the presence of a significant intramolecular ironboron interaction, which was thought to have an impact on the boron centred Lewis acidity. As a result, the binding of donor solvent molecules (acetone, THF, MeCN) was not observed in contrast to the related compound  $B(C_6F_5)_3$ . Alternatively, the Lewis acidity of the  $-B(C_6F_5)_2$  group was demonstrated by electrochemical analysis of the compound, which revealed a ferrocene/ferrocenium oxidation potential of +450 mV relative to ferrocene itself, indicative of a strong electron-withdrawing effect of the boryl group on the ferrocene moiety. Treatment with a stronger base in the form of trimethylphosphine (PMe<sub>3</sub>), however, was sufficient to bring about coordination to the Lewis acidic boryl moiety, evident in the X-ray crystal structure showing PMe<sub>3</sub> linked to tetrahedral boron.

Similarly, the diborylated ferrocene **XXXIII** was shown to bind two molecules of trimethylphosphine in a monodentate manner (one to each boron centre), on the evidence of X-ray diffraction studies on the solid, and NMR measurements in solution. However, unlike the mono-boryl system, the disubstituted ferrocene was shown to coordinate weak donors such as acetonitrile at room temperature. This behaviour is consistent with a receptor of greater Lewis acidity (relative to the monoboryl analogue), and was attributed to a weaker iron-boron interaction, due to the sharing of electron density at iron between the two boron centres.

More recently, an interesting report concerning the coordination of a Lewis basic moiety to a diborylated ferrocene has been made by Wagner and colleagues.<sup>60</sup> The Lewis acid-Lewis base adduct between 1,1'-bis(dibromoboryl)ferrocene and 3,3', 4,4'-tetramethyl-1,1'-diphosphaferrocene (**XXXIV**, Scheme 1.6) was characterised by multinuclear variable-temperature NMR spectroscopy and X-ray diffraction studies.



Scheme 1.6 1:1 adduct formation XXXIV, between 1,1'-bis(dibromoboryl)ferrocene and 3,3', 4,4'-tetramethyl-1,1'-diphosphaferrocene.

Employing one of the most strongly Lewis acidic ferrocene derivatives available, the formation of either a donor-acceptor type macrocycle (with a 1:1 stoichiometry), or a polymeric species (from -P-Fc-P-B-Fc-B- type linking) is conceivable. However, variable temperature <sup>11</sup>B and <sup>31</sup>P NMR spectroscopy in  $d_8$ -toluene indicated significant variations in chemical shifts over a temperature range of -60°C to 30°C when the Lewis acid and base were mixed in equimolar proportions. This observation was attributed to average values of all components present in the reaction mixture, with the adduct formation predominating at lower temperatures. In the solid state, only the 1:1 complex XXXIV, featuring a single dative P-B bond was observed. The explanation for this unexpected result was that formation of the Lewis acid-base P-B interaction had the effect of reducing both the Lewis basicity and Lewis acidity of the remaining phosphorus and boron centres respectively, to the extent that further coordination was not possible.

#### 1.2.3.3 Receptor systems featuring alternative Lewis acidic elements

In addition to boron, the inherent Lewis acidity of many other elements has been exploited in the development of receptor systems for anion and Lewis base recognition. This is manifested in the literature by numerous reports of varying receptor frameworks containing different Lewis acidic centres. Selected examples most relevant to anion and Lewis base complexation are therefore brought to attention at this point.

The use of tin-based macrocyclic receptors for the recognition of anionic species has been reported by Newcombe *et. al.* in the synthesis of organotin cryptands for halide encapsulation.<sup>61</sup> The macrobicyclic tin Lewis acid systems **XXXV** and **XXXVI**, illustrated in Figure 1.17 were found to successfully bind both fluoride and chloride in 1:1 stoichiometry, with chloride being bound by the larger macrocyclic receptor (**XXXVI**, n = 8), and fluoride by the smaller host (**XXXV**, n = 6).





Characterisation of the fluoride and chloride complexes was provided by Xray crystallography and solid state <sup>119</sup>Sn NMR spectroscopy. The X-ray diffraction data of the halide complexes revealed that the anions were bound within the host cavities with differing modes of interaction. The host-guest complex featuring chloride indicated that one of the Lewis acidic tin atoms binds the anion strongly, with the other interacting minimally with the anion. The solid state structure of the fluoride adduct, however, displayed the anionic guest shared by both acidic tin atoms within the cavity (bidentate binding). From solution NMR studies, determination of the binding constants indicated that fluoride binding was significantly stronger than the analogous binding of chloride in C<sub>2</sub>D<sub>2</sub>Cl<sub>4</sub> [ $K \sim 1-2 \times 10^4$  M<sup>-1</sup> (F<sup>-</sup>) c.f.  $K \sim 7$  M<sup>-1</sup> (CF)].

The idea of anion complexation using bidentate group 14 based Lewis acidic hosts has been investigated in a synthetic study by Tamao and colleagues. Initial studies revolved around the synthesis and structural analysis of novel pentacoordinate anionic bis-siliconates.<sup>62</sup> However, it was later realised that the precursors to these compounds behave as bidentate hosts for inclusion of the fluoride ion. Thus, the binding properties of three different *ortho*-bis(fluorosilyl)benzenes with fluoride were analysed *via* <sup>1</sup>H and <sup>19</sup>F NMR spectroscopy; one example of which is shown in Scheme 1.7 (XXXVII), with the anion-chelating product XXXVIII resulting from fluoride addition.<sup>63</sup>



Scheme 1.7 The bidentate binding of fluoride by one of the *ortho*bis(fluorosilyl)benzenes reported by Tamao *et. al.* 

In addition to the receptor **XXXVII**, depicted in Scheme 1.7, two other derivatives were investigated by varying the substitution pattern at silicon  $[o-C_6H_4(SiF_3)(SiPh_2F)$  and  $o-C_6H_4(SiPh_2)(SiPh_2F)]$ , enabling receptors of different Lewis acidic strength, and therefore different fluoride binding capabilities to be tested. The extent of binding was established by the determination of estimated complexation constants for each of the receptors, obtained from competition experiments with a receptor of known binding constant, since the fluoride binding constants were too large to measure directly by NMR titration studies. The results indicated disparate binding strengths in acetone- $d_6$  for the three bidentate receptors  $[K = 5.9 \times 10^5 \text{ M}^{-1} \text{ for}$  $o-C_6H_4(SiPh_2)(SiPh_2F)$ , 5.9 x 10<sup>7</sup> M<sup>-1</sup> for **XXXVII**, and  $K > 1.1 \times 10^9 \text{ M}^{-1}$  for  $o-C_6H_4(SiF_3)(SiPh_2F)$ , but more importantly, that these receptors were among the strongest organic hosts for the inclusion of fluoride in an organic solvent at the time of the report.

Another group to have made use of the *ortho*-phenylene Lewis acid framework is that of Gabbaï. Rather than using a silicon based Lewis acid, efforts have concentrated on the molecular recognition of basic substrates possessing terminal oxo groups by a chelating mercury-containing Lewis acid XXXIX,<sup>64</sup> as shown in Scheme 1.8.



Scheme 1.8 The host-guest chemistry of 1,2-bis(chloromercurio)tetrafluorobenzene.

In particular, XXXIX was found to coordinate acetone (XL, Scheme 1.8), in addition to DMF and DMSO through bidentate coordination of the carbonyl oxygen to both Lewis acidic mercury centres. Host-guest solution studies further revealed that the incremental addition of DMSO or DMF to an acetone solution of the Lewis acid resulted in the displacement of the acetone guest by the alternative oxo species, as shown by the <sup>199</sup>Hg NMR chemical shift change. In support of this observation were the stability constants obtained from <sup>199</sup>Hg NMR titration studies [*K* (DMSO) > *K* (DMF)], which follow the relative donor strength associated with the guest species (DMSO > DMF > acetone). Confirmation of the structures of the acetone and DMF adducts was obtained by X-ray diffraction, which in both cases displayed bidentate coordination of the carbonyl oxygen to both Lewis acidic mercury centres.

Hawthorne and Zheng have also employed Lewis acidic mercury centres in the development of elaborate carborane-supported multidentate macrocyclic Lewis acid hosts systems.<sup>65</sup> The macrocycles investigated comprised three or more mercury

atoms interlinked by the same number of icosahedral *ortho*-carborane cages; some examples of these "mercuracarborands" are shown in Figure 1.18.



Figure 1.18 Novel mercuracarborands for halide encapsulation, as reported by Hawthorne and Zheng, 1997.

The logic in the choice of mercury as the Lewis acid centre was three-fold. Firstly, in diorganomercury [Hg(II)] species, the formation of two essentially colinear  $\sigma$  bonds allows the Lewis acidity of the metal centre to be maintained through a pair of perpendicular empty p-orbitals. Secondly, the linear geometry about Hg(II) allows its inclusion in cyclic structures to afford host species with relatively large cavities. Finally, the fact that Hg(II) species are stable in the presence of air and water was another aspect taken into consideration. The Lewis acidity of the mercury centres together with the electron withdrawing effects of the carborane cages enabled both the binding of chloride, and the binding of two iodide ions to the cyclic tetrameric system (Fig. 1.18). These halide coordination studies were closely followed by <sup>199</sup>Hg NMR spectroscopy, and confirmed by single crystal X-ray diffraction studies, in which the bound chloride was shown to interact equally with all four Hg centres, as were the two iodide ions located above and below the plane of the mercuracarborand ring. Further modification of the basic receptor framework led to formation of a range of macrocyclic Lewis acids, some of which were found to bind weakly coordinating bases such as the  $B_{10}H_{10}^{2-}$  anion.

Tsunoda and Gabbaï have also reported Lewis base binding by polyfunctional organomercurials, including the hexacoordination of dimethyl sulphide to a trimeric perfluoro-*ortho*-phenylene mercury receptor **XLI**, as illustrated in Figure 1.19.<sup>66</sup> This particular report was a strictly structural study with X-ray crystallography being employed for the analysis of two different modes of coordination of the Lewis basic dimethylsulphide molecule to the tridentate receptor.



Figure 1.19 XLI: A macrocyclic polydentate organomercurial; and XLII: a bidentate indium based Lewis acid for diazine recognition.

In the first instance of XLI, slow concentration of a dimethyl sulphide solution of the receptor yielded crystals in which four molecules of Me<sub>2</sub>S were coordinated to one receptor unit. Two of these Lewis basic guests were bound in a tridentate fashion (above and below the plane of the macrocycle), with the other two Me<sub>2</sub>S molecules binding in a monodentate arrangement. Further experiments involving treatment of the receptor with excess quantities of Me<sub>2</sub>S, and subsequent crystallisation led to the formation of an adduct in which one Me<sub>2</sub>S molecule was hexacoordinated to two receptor units, as shown by X-ray diffraction studies. This represented an unusually high coordination number for a neutral dialkyl sulphide molecule, which is typically thought to act as a terminal or bidentate bridging ligand. The coordination properties of these receptors have also been further investigated with respect to weakly coordinating organic substrates (*e.g.* aldehydes/ketones and arenes).<sup>67</sup>

Other studies by Gabbaï and colleagues have revolved around the synthesis and Lewis base recognition properties of a dimeric ortho-phenyleneindium bromide, XLII (Figure 1.19).<sup>68</sup> Binding studies involved treatment of the bidentate Lewis acid with a series of diazines, namely pyridazine (1,2-diazine), phthalazine (2,3benzodiazine), pyrimidine (1,3-diazine) and pyrazine (1,4-diazine), and monitoring of the progress of binding by <sup>1</sup>H NMR. The results indicated a specific host-guest interaction between the dimeric indium receptor, and either pyridazine or phthalazine. Thus it was concluded that XLII was a selective receptor for 1,2-diazines. Determination of stability constants from <sup>1</sup>H NMR titrations revealed significant binding interactions in  $d_8$ -THF [K = 80 M<sup>-1</sup> (pyridazine) and K = 1000 M<sup>-1</sup> (phthalazine)], and confirmation of the mode of binding was provided by X-ray crystallography. The host-guest adduct of the receptor with phthalazine (2,3benzodiazine), showed complexation of two phthalazine molecules, one in bidentate fashion, the other binding to only one indium in a monodentate fashion. More recent reports by this group have included Lewis base binding by receptors possessing Lewis acidic tin and gallium receptors.<sup>69</sup>

Uhl, Hannermann and Saak have sought to exploit the binding properties of a bifunctional Lewis acidic host in the form of the methylene bridged dialuminium compound XLIII.<sup>70</sup> The potential of such a compound to act as a chelating Lewis

acid was shown by binding studies involving  $NO_3^-$  and  $NO_2^-$  sources, as summarised in Scheme 1.9.



Scheme 1.9 Anion chelation of nitrate and nitrite by a bidentate dialuminium Lewis acid, as reported by Uhl, Hannermann and Saak, 1998.

Reactions of the bifunctional Lewis acid with a nitrate source yielded a complementary acid/base chelate species in which the nitrate anion is bound by two oxygen atoms to form a six-membered heterocycle (XLIV, Scheme 1.9). This interaction was found to be particularly favourable since the Al<sup>…</sup>Al separation in the Lewis acid is comparable to that of the O<sup>…</sup>O separation in nitrate. Furthermore, reaction of the Lewis acid with sodium nitrite, yielded the nitrite-bound five-membered heterocycle XLV. Both adducts were characterised by X-ray diffraction, and this was believed to be the first time that chelating Lewis acids featuring coordinatively unsaturated group 13 centres had been successfully used for the selective coordination of bidentate anions, with confirmation by crystal structure analysis.

#### 1.2.4 Methyl anion abstraction (olefin polymerisation catalysis)

The large amount of interest in this particular branch of Lewis acid coordination chemistry stems from species such as methylalumoxane (MAO) and  $B(C_6F_5)_3^{71}$  as hydride and alkide abstractors, which take part in the generation of the active catalytic species required for olefin polymerisation. Their general role is to act as a co-catalyst, whereby they generate the active cationic species, formed by the abstraction of the methyl anion,  $CH_3^-$ . Further, related examples can be found in the recent literature,<sup>71,72</sup> however, this section will focus on selected examples of alternative boron based co-catalysts with alkide abstraction properties.

A number of research groups have contributed significantly over the last ten years to the development of replacement co-catalysts for efficient olefin polymerisation. Both Marks and Piers have independently reported different bifunctional boron systems bridged by one atom, in which the boron-bound substituents are highly electron withdrawing  $-C_6F_5$  moieties (Figure 1.20).<sup>73,74</sup>





The aim of the Marks group in the synthesis of species XLVI, was to employ such boranes as precursors to weakly coordinating anions (formed by hydride abstraction/binding). The bidentate coordination of H<sup>-</sup> to XLVI was found to give a stable anionic acid/base complex which when partnered by an active cationic catalyst, led to significant polymerisation activity towards ethylene  $[1.0(2) \times 10^6 \text{ g of}]$  polyethylene (mol of Zr cat)<sup>-1</sup> h<sup>-1</sup> atm<sup>-1</sup>].

The alkene based system **XLVII** developed by Piers, Marder and co-workers was prepared with the hope that binding of the methyl anion would occur in a chelating fashion. It was thought that such anion chelation might improve catalytic properties by allowing an increased delocalisation of negative charge in the anionic adduct over the alkene unit as well as the two boron centres. The extent of interaction between the anionic adduct and the active cationic species would then be diminished. However, <sup>1</sup>H NMR spectroscopy indicated that abstraction of CH<sub>3</sub><sup>-</sup> from the Cp<sub>2</sub>Zr(CH<sub>3</sub>)<sub>2</sub> catalyst precursor occurred *via* coordination to only one boron centre, creating an anionic adduct that was susceptible to undesirable decomposition at ambient temperatures.

Mindful of these results, Piers, Marder and colleagues aimed to increase the possibility of methide chelation by increasing the distance between the boron atoms and employing an *ortho*-substituted backbone (Figure 1.21, XLVIII and XLIX).<sup>75,76</sup> Compound XLIX (X = F) was characterised by X-ray crystallography, which revealed the intramolecular boron-boron distance to be 3.138(2)Å. This distance appears large enough for the bidentate coordination of small anions, a mode of coordination which was confirmed by <sup>11</sup>B NMR spectroscopic monitoring of reactions with F<sup>-</sup> and OH<sup>-</sup>.



Figure 1.21 1,2-phenylene-bridged systems, XLVIII and XLIX, and a diboraanthracene analogue for methide abstraction, L.

With regards to methide abstraction for olefin polymerisation catalysis, **XLVIII** and **XLIX** were shown to successfully abstract  $CH_3^-$  from  $Cp_2Zr(CH_3)_2$ , with the anionic adduct featuring an equilibrating mixture of species created by  $-CH_3$  and  $-C_6F_5$  transfer between boron centres, *i.e.* methide chelation was not observed. Subsequent reports have shown the perfluorinated derivative to be an effective co-initiator in the polymerisation of isobutene by the chelating abstraction of chloride and methoxide from cumyl chloride (ClCMe<sub>2</sub>Ph) and cumyl methyl ether (MeOCMe<sub>2</sub>Ph).<sup>77</sup>

A common observation made by the groups of both Piers and Marks in investigations involving *ortho*-1,2-dihaloboryl derivatives of benzene was that these compounds were susceptible to a condensation reaction forming a 9,10-diboraanthracene derivative.<sup>75,76,78</sup> With this in mind, Marks *et. al.* further modified the fluoroarylborane architecture by incorporation of  $-C_6F_5$  groups to form the diboraanthracene Lewis acid L.<sup>78</sup> The increased Lewis acidity together with the potential of delocalisation of negative charge in the anionic adduct meant that this system was particularly effective in abstracting methide from the metallocene catalyst

 $Cp_2Zr(CH_3)_2$  to yield an active catalytic ion pair. Similar observations were also reported by Piers and Marder, in which anion abstraction was found to occur in a nonchelating fashion, due to the parallel orientation of the vacant boron  $p_z$ -orbitals preventing anion chelation.

#### 1.3 Aims of current research

The objectives for the research described in this thesis were four-fold:

(i) In view of the large number of receptor species for anions reported that utilise hydrogen bonding motifs (with or without an electrostatic component), it was decided to synthesise and probe the anion complexation properties of the lesser investigated boron-based Lewis acid systems. The syntheses of mono- and bifunctional Lewis acid systems was to be attempted, and their modes of anion coordination monitored by spectroscopic and structural methods.

(ii) Furthermore, it should prove possible to manipulate the substituents about boron to tune its Lewis acidity, to the extent that specific anion recognition can be accomplished. Given the selectivity of ferroceneboronic acid for fluoride (as reported by Shinkai *et. al.*<sup>79</sup>) the development of boronic esters which might display similar binding behaviour, and can be monitored by NMR and electrochemical methods, is an attractive target.

(iii) In order to gain a clearer understanding of the anion binding process, it might prove advantageous to monitor binding experiments by a variety of methods.

Therefore, the development of receptor systems featuring handles for alternative monitoring techniques (such as infrared and fluorescence spectroscopy for example), might allow different routes to anion detection, and provide further explanation as to the mode of anion coordination and chemical behaviour of the resultant host-guest species.

(iv) In addition to specific anion recognition, the field of molecular sensing has also witnessed significant interest in the literature. The possibility of whole acid sensing, and in particular, the sensing of hydrogen fluoride appears feasible by modification of Lewis acid receptor systems to include an additional Lewis base function (*e.g.* a tertiary amine). Hydrogen fluoride has been shown to be a by-product of the hydrolysis of chemical warefare agents [*e.g.* sarin (GB)],<sup>80</sup> and in industry is a much-used but highly toxic substance. Hence the detection/monitoring of such a substance by an appropriate receptor system would be of major significance.

#### 1.4 References for Chapter One

- 1. C. J. Pedersen, J. Am. Chem. Soc., 1967, 89, 7017.
- 2. R. W. Alder, P.S. Bowman, W.R.S. Steele, D. R. Winterman, Chem. Commun., 1968, 723.
- 3. C. H. Park, H. E. Simmons, J. Am. Chem. Soc., 1968, 90, 2431.
- 4. J. M. Lehn, E. Graf, J. Am. Chem. Soc., 1976, 98, 6403.
- 5. J. W. Steed and J. L. Atwood, in *Supramolecular Chemistry*, Wiley, New York, 2000, pp 198-249.
- P. D. Beer, P. A. Gale, D. K. Smith, in *Supramolecular Chemistry*, OCP (74), Oxford University Press, 1999, pp 31-42.
- 7. See, for example: F. P. Schmidtchen, M. Berger, Chem. Rev., 1997, 97, 1609;
  P. D. Beer, P. A. Gale, Angew. Chem., Int. Ed., 2001, 40, 486.
- 8. J. J. Lavigne, E. V. Anslyn, Angew. Chem., Int. Ed., 2001, 40, 3118.
- 9. T. S. Snowden, E. V. Anslyn, Curr. Opin. Chem. Biol., 1999, 3, 740.
- 10. P. A. Gale, J. L. Sessler, Chem. Commun., 1998, 1.
- 11. M. M. G. Antonisse, D. N. Reinhoudt, Chem. Commun., 1998, 443.
- 12. J. L. Atwood, K. T. Holman, J. W. Steed, Chem. Commun., 1996, 1401.
- See, for example: P. D. Beer, Acc. Chem. Res., 1998, 31, 71; P. D. Beer, P. A.
   Gale, G. Z. Chen, Coordination Chem. Rev., 1999, 185-186, 3.
- See, for example: B. Dietrich, J. Guilhem, J. M. Lehn, C. Pascard, E. Sonveaux, *Helv. Chim. Acta*, 1984, 67, 91; B. Dietrich, J.M. Lehn, J. Guilhem, C. Pascard, *Tetrahedron Lett.*, 1989, 30, 31, 4125 and references cited therein.
- 15. C. R. Bondy, P. A. Gale, S. J. Loeb, Chem. Commun., 2001, 729.
- J. L. Sessler, T. D. Mody, D. A. Ford, V. Lynch, Angew. Chem., Int. Ed. Engl., 1992, 31, 452.

- See, for example: K. Tamao, T. Hayashi, Y. Ito, J. Organomet. Chem., 1996,
   506, 85; F. P. Gabbaï, Angew. Chem. Int. Ed., 2003, 42, 2218.
- X. G. Yang, C. B. Knobler, Z. P. Zheng, M. F. Hawthorne, J. Am. Chem. Soc., 1994, 116, 7142.
- K. Nozaki, M. Yoshida, H. Takaya, Angew. Chem., Int. Ed. Engl., 1994, 33, 2453.
- 20. G. E. Herberich, A. Fischer, D. Wiebelhaus, Organometallics, 1996, 15, 3106.
- 21. S. Aldridge, C. Bresner, I. A. Fallis, S. J. Coles, M. B. Hursthouse, Chem. Commun., 2002, 740.
- See, for example: J. J. He, F. A. Quiocho, Science, 1991, 251, 1479; Z. F. Kanyo, D. W. Christianson, J. Biol. Chem., 1991, 266, 4246.
- 23. B. Metz, J. M. Rosalky, R. Weiss, J. Chem. Soc., Chem. Commun., 1976, 533.
- See, for example: F. Suet, H. Handel, *Tetrahedron Lett.*, 1984, 25, 645; R. J.
   Motekaitis, A. E. Martell, I. Murase, *Inorg. Chem.*, 1986, 25, 938.
- S. D. Reilly, G. R. K. Khalsa, D. K. Ford, J. R. Brainard, B. P. Hay, P. H. Smith, *Inorg. Chem.*, 1995, 34, 569.
- 26. S. Mason, J. M. Llinares, M. Morton, T. Clifford, K. Bowman-James, J. Am. Chem. Soc., 2000, 122, 1814.
- 27. J. L. Sessler, D. A. Ford, M. J. Cyr, H. Furuta, J. Chem. Soc., Chem. Commun., 1991, 1733.
- J. L. Sessler, M. J. Cyr, V. Lynch, E. McGhee, J. A. Ibers, J. Am. Chem. Soc., 1990, 112, 2810; M. Shinoya, H. Furuta, V. Lynch, A. Harriman, J. L. Sessler, J. Am. Chem. Soc., 1992, 114, 5714.
- 29. See, for example: J. L. Sessler, T. D. Mody, D. A. Ford, V. Lynch, Angew. Chem., Int. Ed. Engl., 1992, 31, 452; J. L. Sessler, M. Cyr, H. Furuta, V. Král,

- T. Mody, T. Morishima, M. Shinoya, S. Weghorn, Pure Appl. Chem., 1993, 65, 393.
- C. B. Black, B. Andrioletti, A. C. Try, C. Ruiperez, J. L. Sessler, J. Am. Chem. Soc., 1999, 121, 10438.
- 31. J. L. Sessler, A. Gebauer, P. A. Gale, Gazz. Chim. Ital., 1997, 127, 723.
- 32. H. Miyaji, P. Anzenbacher Jr., J. L. Sessler, E. R. Bleasdale, P. A. Gale, Chem. Commun., 1999, 1723.
- P. A. Gale, L. J. Twyman, C. I. Handlin, J. L. Sessler, *Chem. Commun.*, 1999, 1851.
- See, for example: P. Anzenbacher Jr., K. Jursiková, V. M. Lynch, P. A. Gale,
   J. L. Sessler, J. Am. Chem. Soc., 1999, 121, 11020; L. Bonomo, E. Solari, G.
   Toraman, R. Scopelliti, M. Latronico, C. Floriani, Chem. Commun., 1999, 2413.
- 35. S. Camiolo, P. A. Gale, Chem. Commun., 2000, 1129.
- 36. P. D. Beer, P. A. Gale, D. Hesek, Tetrahedron Lett., 1995, 36, 767.
- W. B. Farnham, D. C. Roe, D. A. Dixon, J. C. Calabrese, R. L. Harlow, J. Am. Chem. Soc., 1990, 112, 7707.
- 38. M. A. Hossain, K. Ichikawa, Tetrahedron Lett., 1994, 35, 45, 8393.
- K. Ichikawa, A. Yamamoto, M. A. Hossain, *Chem. Lett.*, 1993, 12, 2175 and references cited therein.
- 40. See, for example: K. Kavallieratos, S. R. de Gala, D. J. Austin, R. H. Crabtree, J. Am. Chem. Soc., 1997, 119, 2325; S. R. Collinson, T. Gelbrich, M. B. Hursthouse, J. H. R. Tucker, Chem. Commun., 2001, 555 and references cited therein.

- 41. F. P. Schmidtchen, M. Berger, *Chem. Rev.*, 1997, 97, 1609 and references cited therein.
- 42. B. Dietrich, T. M. Fyles, J. M. Lehn, L. G. Pease, D. L. Fyles, J. Chem. Soc., Chem. Commun., 1978, 934.
- See, for example: F. P. Schmidtchen, Chem. Ber., 1980, 113, 2175; G.
   Mueller, J. Riede, F. P. Schmidtchen, Angew. Chem., 1988, 100, 1574.
- 44. For representative examples of the binding of acetate and related anionic/neutral systems by hydrogen bond donors, see: E. Fan, S. A. Van Arman, S. Kincaid, A. D. Hamilton, J. Am. Chem. Soc., 1993, 115, 369; P. D. Beer, Z. Chen, A. J. Goulden, A. Craydon, S. E. Stokes, T. Wear, J. Chem. Soc., Chem. Commun., 1993, 1834; T. R. Kelly, M. H. Kim, J. Am. Chem. Soc., 1994, 116, 7072; M. P. Hughes, B. D. Smith, J. Org. Chem., 1997, 62, 4492, P. D. Beer, V. Timoshenko, M. Maestri, P. Passaniti, V. Balzani, Chem. Commun., 1999, 1755.
- 45. C. R. Bondy, P. A. Gale, S. J. Loeb, Chem. Commun., 2001, 729.
- 46. D. F. Shriver, M. J. Biallas, J. Am. Chem. Soc., 1967, 89, 1078.
- 47. H. E. Katz, J. A. Chem. Soc., 1985, 107, 1420.
- 48. H. E. Katz, J. Org. Chem., 1985, 50, 5027.
- 49. H. E. Katz, Organometallics, 1987, 6, 1134.
- 50. S. Jacobson, R. Pizer, J. Am. Chem. Soc., 1993, 115, 11216.
- 51. S. Aldridge, I. A. Fallis, S. T. Howard, Chem. Commun., 2001, 231.
- 52. G. E. Herberich, A. Fischer, D. Wiebelhaus, Organometallics, 1996, 15, 3106.
- 53. H. E. Katz, J. Org. Chem., 1989, 54, 2179.
- 54. K. Nozaki, M. Yoshida, H. Takaya, Angew. Chem. Int. Ed., Engl., 1994, 33, 23/24, 2452.

- 55. K. Nozaki, T. Tsutsumi, H. Takaya, J. Org. Chem., 1995, 60, 6668.
- 56. D. H. Emslie, W. E. Piers, M. Parvez, Angew. Chem. Int. Ed., 2003, 42, 1251.
- 57. I. Ghesner, W. E. Piers, M. Parvez, R. McDonald, Organometallics, 2004, 23, 3085.
- 58. B. E. Carpenter, W. E. Piers, M. Parvez, G. P. A. Yap, S. J. Rettig, *Can. J. Chem.*, 2001, **79**, 857.
- 59. B. E. Carpenter, W. E. Piers, R. Mcdonald, Can. J. Chem., 2001, 79, 291.
- 60. M. Scheibitz, M. Bolte, H. W. Lerner, M. Wagner, Organometallics, 2004, 23, 3556.
- 61. M. Newcombe, J. H. Horner, M. T. Blanda, P. J. Squattrito, J. Am. Chem. Soc., 1989, 111, 6294 and references cited therein.
- K. Tamao, T. Hayashi, Y. Ito, M. Shiro, J. Am. Chem. Soc., 1990, 112, 2422;
  K. Tamao, T. Hayashi, Y. Ito, M. Shiro, Organometallics, 1992, 11, 2099.
- 63. K. Tamao, T. Hayashi, Y. Ito, J. Organomet. Chem., 1996, 506, 85.
- 64. M. Tschinkl, A. Schier, J. Riede, F. P. Gabbaï, Organometallics, 1999, 18, 1747.
- 65. M. F. Hawthorne, Z. Zheng, Acc. Chem. Res., 1997, 30, 7, 267.
- 66. M. Tsunoda, F. P. Gabbaï, J. Am. Chem. Soc., 2003, 125, 10492.
- 67. M. R. Haneline, R. E. Taylor, F. P. Gabbaï, Chem. Eur. J., 2003, 9, 5188.
- 68. F. P. Gabbaï, A. Schier, J. Riede, M. J. Hynes, Chem. Commun., 1998, 897.
- 69. See, for example: J. D. Hoefelmeyer, F. P. Gabbaï, Chem. Commun., 2003, 712.
- 70. W. Uhl, F. Hannermann, W. Saak, R. Wartchow, Eur. J. Inorg. Chem., 1998, 921.

- 71. See, for example: X. Yang, C. L. Stern, T. J. Marks, J. Am. Chem. Soc., 1994,
  116, 10015; W. E. Piers, T. Chivers, Chem. Soc. Rev., 1997, 26, 345; L. Luo,
  T. J. Marks, Topics in Catalysis, 1999, 7, 97 and references cited therein.
- See for example: E. Y. X. Chen, T. J. Marks, Chem. Rev., 2000, 100, 1391;
  W. E. Piers, G. J. Irvine, V. C. Williams, Eur. J. Inorg. Chem., 2000, 2131.
- 73. L. Jia, X. Yang, C. L. Stern, T. J. Marks, Organometallics, 1994, 13, 3755.
- K. Kohler, W. E. Piers, A. P. Jarvis, S. Xin, Y. Feng, A. M. Bravakis, S. Collins, W. Clegg, G. P. A. Yap, T. B. Marder, *Organometallics*, 1998, 17, 3557.
- V. C. Williams, W. E. Piers, W. Clegg, M. R. J. Elsegood, S. Collins, T. B. Marder, J. Am. Chem. Soc., 1999, 121, 3244.
- V. C. Williams, C. Dai, Z. Li, S. Collins, W. E. Piers, W. Clegg, M. R. J. Elsegood, T. B. Marder, *Angew. Chem. Int. Ed.*, 1999, 38, 24, 3695.
- 77. S. P. Lewis, N. J. Taylor, W. E. Piers, S. Collins, J. Am. Chem. Soc., 2003, 125, 14686.
- M. V. Metz, D. J. Schwartz, C. L. Stern, P. N. Nickias, T. J. Marks, Angew. Chem. Int. Ed., 2000, 39, 7, 1312.
- C. Dusemond, K. R. A. Samankumara Sandanayake, S. Shinkai, J. Chem. Soc., Chem. Commun., 1995, 333; H. Yamamoto, A. Ori, K. Ueda, C. Dusemond, S. Shinkai, Chem. Commun., 1996, 407.
- See for example: H. Sohn, S. Létant, M. J. Sailor, W. C. Trogler, J. Am. Chem. Soc., 2000, 122, 5399; S. W. Zhang, T. W. Swager, J. Am. Chem. Soc., 2003, 125, 3420 and references cited therein.

## **Chapter Two**

## **Experimental Techniques**

#### 2.1 Manipulation of air-sensitive compounds

The air and moisture sensitive nature of various compounds described in this thesis has made it necessary to employ specific inert atmosphere and high vacuum techniques rather than orthodox bench top methods. As a result, a basic introduction to the synthesis and handling of such compounds is required, and is presented at this stage. For a more in depth discussion about such methods, previous literature reviews and books<sup>1,2</sup> provide substantial further information.

## 2.1.1 Inert atmosphere techniques

The most widespread technique used in the manipulation of air and moisturesensitive compounds is the handling of such species under an inert atmosphere. The most common choices are argon and nitrogen gas. During this project, two methods utilising such inert-gas methods were employed: Schlenk line techniques, in which compounds of an air/moisture-sensitive nature can be handled on the bench-top using suitably adapted glassware, and the use of a specially designed air-sealed unit or glove box, in which sensitive materials are accessed by sealed gloves.

The convenient Schlenk technique approach means that both large and small quantities of air/moisture-sensitive chemicals can be manipulated without risk of decomposition or side reaction. The set-up of the Schlenk line used for all of the research contained within this thesis is illustrated in Figure 2.1. The Schlenk line consists of two Pyrex glass manifolds, one of which is connected to the inert gas supply (typically argon), with the second tube connected to a mechanical vacuum pump. In addition, the ground glass joints and two-way stopcocks were lubricated with 'Dow-Corning High Vacuum' grease providing airtight containment.



Figure 2.1 A typical Schlenk line.

Evacuation was achieved by use of an oil-sealed rotary pump in conjunction with a liquid nitrogen cooled trap to collect and prevent volatiles from contaminating the vacuum pump. Attachment of a Pirani pressure gauge to the vacuum manifold allowed pressures of evacuation to be monitored (typically 10<sup>-2</sup> Torr). The inert gas supply, typically argon, was introduced to the Schlenk line from a cylinder prior to passing the gas through a scavenger column packed with molecular sieves to remove any traces of moisture within the gas supply. In order to avoid excessive pressure, a mercury bubbler was attached to the inert gas outlet. The exposure of the apparatus to either vacuum or inert gas is performed by the use of two-way taps. Thus, removal of atmospheric gases and the production of an inert atmosphere within Schlenk glassware involved evacuation of the glassware, followed by the filling of the apparatus with inert argon gas. This 'pump-and-purge' cycle is usually repeated at least three times to achieve the desired oxygen- and moisture-free environment. The transfer of solutions and liquids between Schlenk apparatus was accomplished using cannulae and syringes in conjunction with rubber septa to seal vessels from the external atmosphere.

During the course of this work, it was also necessary to handle air-sensitive solids for which Schlenk line and cannulae techniques were unsuitable. Therefore, such operations were carried out using a 'Saffron Scientific Omega' glove box. The glove box design consists of an air-tight stainless steel unit with a toughened glass window. Apparatus and compounds were introduced through an evacuable side-port, again subjected to the pump-and-purge routine prior to box entrance. Once entered, two neoprene gloves allow access and manipulation of apparatus and compounds. The glove box atmosphere (usually nitrogen) was maintained by a B.O.C. cylinder, the contents of which were circulated internally through catalyst, molecular sieve and solvent scrubbing columns, thus providing an atmosphere with oxygen and moisture levels of less than 5 ppm and 10 ppm respectively.<sup>3</sup>

## 2.1.2 High vacuum techniques

For processes such as vacuum sublimation or removal of trace solvent from compounds, the basic rotary pump on a Schlenk line provides insufficient vacuum. As a result, these procedures were carried out on a high vacuum line. This alternative system was constructed from a Pyrex glass manifold with Young's greaseless stopcocks. Evacuation in this case was carried out by combination of mercury diffusion and a rotary pump, enabling pressures of *ca.*  $10^{-4}$  Torr accessible. In order to monitor such pressures a high voltage Tesla coil was used which produced a discharge at pressures between 1 and  $10^{-3}$  Torr. Contamination of the pump by volatile

substances was again prevented by incorporating a liquid nitrogen cooled trap in the set-up.

#### 2.2 Physical measurements

#### 2.2.1 NMR Spectroscopy

NMR spectra were measured on a Bruker AM-400 or Jeol Eclipse 300 Plus FT-NMR spectrometer. Residual protons of solvent were used for reference for <sup>1</sup>H and <sup>13</sup>C NMR, while a sealed tube containing a solution of ["Bu<sub>4</sub>N][B<sub>3</sub>H<sub>8</sub>] in CDCl<sub>3</sub> was used as an external reference for <sup>11</sup>B NMR. In addition, CFCl<sub>3</sub> was used as an external reference for <sup>19</sup>F NMR. Sample preparation involved generating an inert atmosphere within a Young's NMR tube ('pump-and-purge' method) followed by solution transfer *via* cannula.

#### 2.2.2 Infrared Spectroscopy

Infrared spectra were measured by pressing each compound into a disk with a ten-fold excess of dried KBr, or as a solution contained within a solution infrared cell. KBr disks of air-sensitive materials were prepared in the glove box, in which case the KBr was dried by heating under high vacuum before use. Spectra were recorded on a Perkin-Elmer 1600 Series FTIR spectrometer or a Nicolet 500 FT-IR spectrometer.

#### 2.2.3 Mass Spectrometry

Mass spectra were measured by the EPSRC National Mass Spectrometry Service Centre, University of Wales Swansea and by the departmental service. Perfluorotributylamine (EI) and polyethylenimine (ES) were used as the standards for the high resolution mass spectra.

#### 2.2.4 UV/Vis Spectroscopy

UV spectra were measured using a Perkin-Elmer Lambda 20 UV/Vis spectrometer. Solution samples of air-sensitive materials were prepared in a specially designed steel unit under a continuous flow of argon.

#### 2.2.5 X-ray Crystallography

Data collection was carried out on an Enraf Nonius Kappa CCD diffractometer by the EPSRC National X-ray Crystallography Service, University of Southampton, or on a similar instrument at Cardiff University. Structure solution and refinement for compounds **2a** and **2b** were carried out by Dr. S.J. Coles, University of Southampton. For the remaining crystal structures, structure solution and refinement were carried out by Prof. C. Jones or Dr. Li-Ling Ooi of Cardiff University.

#### 2.2.6 Electrochemistry (Cyclic Voltammetry)

Electrochemical analyses were performed using dried, distilled dichloromethane or acetonitrile as the solvent and 0.1M tetrabutylammonium hexafluorophosphate as supporting electrolyte on an Autolab PGSTAT 12 Potentiometer with a Ag/Ag[NO<sub>3</sub>] reference electrode (BAS Non-aqueous Reference Electrode Kit). Ferrocene was used as an internal standard.

#### 2.2.7 Fluorescence Spectroscopy

Fluorescence spectra were measured using a Perkin-Elmer LS 50B luminescence spectrometer. Solution samples were prepared, and the spectra measured in a Quartz SUPRASIL precision fluorescence cell.

#### 2.2.8 Chemical Analysis

Elemental analyses were performed by Warwick Analytical Services, University of Warwick.

## 2.3 Purification and preparation of essential solvents and reagents

Several compounds prepared during the course of this research were only accessible *via* certain precursors, which were not themselves commercially available. As a result, such starting materials had to be synthesised from readily available reagents, as described in this section. Some of the commercially available reagents were purchased and used without further purification, however, the majority of starting materials and solvents were purified prior to use. The sources and necessary methods of purification for the various compounds used are found in Table 2.1.

# Table 2.1 Chemical sources and purification methods.

Compound	Source	Quoted purity	Method
Reagents	I		
Ferrocene	Alfa	99 %	Used as supplied
	Aesar		
Cymantrene	Strem	98 %	Used as supplied
trans-Stilbene	Lancaster	97 %	Used as supplied
Methane sulphonamide	Avocado	98+ %	Used as supplied
(DHQ) <sub>2</sub> PHAL	Aldrich	95+ %	Used as supplied
(DHQD)2PHAL	Aldrich	95+ %	Used as supplied
Potassium ferricyanide	Aldrich	99 %	Used as supplied
Potassium carbonate	Aldrich	99 %	Used as supplied
Potassium osmate (VI)	Aldrich	a	Used as supplied
dihydrate (K2OsO4.2H2O)			
Sodium sulphite	B.D.H	96 %	Used as supplied
H <sub>2</sub> SO <sub>4</sub>	Fisher	98 %	Used as supplied
HCl $(1.0M \text{ in Et}_2O)$	Aldrich	a	Used as supplied
Sodium hydrogencarbonate	Fisher	99 %	Used as supplied
Magnesium sulphate	Fisher	70 %	Used as supplied
2,5-Dihydroxy-para-quinone	Aldrich	98 %	Heated to 50°C for 3 h
			in vacuo
Catechol	Aldrich	99+ %	Vacuum sublimation
3,5-di-tert-butylcatechol	Aldrich	99 %	Vacuum sublimation
3-Methoxycatechol	Lancaster	98 %	Vacuum sublimation
2-Vinyl-napthalene	Lancaster	95 %	Used as supplied
N-Methyldiethanolamine	Aldrich	99+ %	Used as supplied
Glycidol	Aldrich	96 %	Used as supplied
Piperidine	Aldrich	99 %	Used as supplied
Triethylamine	Alfa	99 %	Dried over sodium wire
	Aesar		
BBr <sub>3</sub>	Aldrich	99+ %	Used as supplied

BF <sub>3</sub> .OEt <sub>2</sub>	Aldrich	'purified'	Used as supplied
<sup>n</sup> BuLi (1.6M in hexanes)	Acros	a	Used as supplied
	Organics		
Chlorotrimethylsilane	Aldrich	98 %	Used as supplied
Tetra-n-butylammonium	Aldrich	98 %	Used as supplied
fluoride hydrate			
Potassium fluoride	Aldrich	99.5 %	Used as supplied
18-Crown-6	Aldrich	99 %	Used as supplied
Silver nitrate	B.A.S	a	Used as supplied
[ <sup>n</sup> Bu <sub>4</sub> N]Br	Avocado	98 %	Used as supplied
KPF <sub>6</sub>	Avocado	98 %	Used as supplied
Solvents			
Toluene	Fisher	99+ %	Heated under reflux over
			sodium followed by
			distillation
Hexanes	Fisher	99+ %	Heated under reflux over
			potassium followed by
			distillation
Petrol (40-60)	Fisher	99+ %	Used as supplied
Dichloromethane	Fisher	99+ %	Heated under reflux over
			$CaH_2$ followed by
			distillation
THF	Fisher	99+ %	Heated under reflux over
			sodium followed by
			distillation
Acetonitrile	Fisher	99+ %	Heated under reflux over
			CaH <sub>2</sub> followed by
			distillation
Diethyl ether	Fisher	99+ %	Heated under reflux over
			sodium followed by
			distillation
2-Methyl-2-propanol	Aldrich	99.5 %	Used as supplied
Ethanol	Fisher	99+ %	Used as supplied

Deuteriated solvents					
Benzene-d <sub>6</sub>	Goss	99.6 atom %	Stored under argon over		
			potassium mirror		
Chloroform-d	Aldrich	99.8 atom %	Stored under argon over		
			flamed-out molecular		
			sieves		
Dichloromethane-d <sub>2</sub>	Goss	99.8 atom %	Stored under argon over		
			flamed-out molecular		
			sieves		
Inert gases					
Argon	B.O.C	a	Used as supplied		
Nitrogen	B.O.C	a	Used as supplied		

#### 2.3.1 Preparation of precursors

## Preparation of Dibromoborylferrocene, FcBBr<sub>2</sub>

Dibromoborylferrocene was prepared by minor modification of the method published by Ruf, Renk and Siebert.<sup>4</sup> BBr<sub>3</sub> (5 cm<sup>3</sup>, 13.25 g, 52.6 mmol) was added slowly to a solution of ferrocene (9.84 g, 52.6 mmol) in toluene (80 cm<sup>3</sup>) and the resulting mixture stirred at 45°C for 3 h. After cooling to room temperature and removal of solvent *in vacuo*, the solid product was extracted into hexanes (3 x 40cm<sup>3</sup>), combining the washings each time by cannula filtration. Concentration of the hexanes solution and cooling to -30°C gave rise to dark red crystals of FcBBr<sub>2</sub> in 51% yield. <sup>1</sup>H and <sup>11</sup>B NMR were in agreement with those reported previously.<sup>4,5</sup>

## Preparation of 1, 1'-Bis(dibromoboryl)ferrocene, fc(BBr<sub>2</sub>)<sub>2</sub>

1, 1'-*Bis*(dibromoboryl)ferrocene was synthesised according to the procedure reported by Appel, Nöth and Schmidt.<sup>6</sup> Boron tribromide (10.2 cm<sup>3</sup>, 27 g, 0.108 mol) was syringed into a solution/slurry of ferrocene (10 g, 53.8 mmol) in hexanes (120 cm<sup>3</sup>), and the mixture heated under reflux for 5 h. Insoluble products were removed *via* cannula filtration from the hot solution affording a dark red solution. Cooling (-30°C) and subsequent concentration of the hexanes solution yielded a dark red crystalline solid, isolated in a combined 62% yield. Characterising data was in the form of <sup>1</sup>H and <sup>11</sup>B NMR, which were in accordance with literature reports.<sup>5, 7</sup>

## Preparation of Dibromoborylcymantrene, $(\eta^5 - C_5H_4BBr_2)Mn(CO)_3$

 $(\eta^5-C_5H_4BBr_2)Mn(CO)_3$  was prepared using a method similar to that used for Fc(BBr\_2)\_2. Both compounds were reported by Siebert and co-workers in 1976.<sup>4,7</sup> ( $\eta^5-C_5H_5$ )Mn(CO)\_3 (2.16 g, 10.5 mmol) was dissolved in hexanes (100 cm<sup>3</sup>) and BBr<sub>3</sub> (1 cm<sup>3</sup>, 2.65 g, 10.5 mmol) added to the solution *via* syringe. The reaction mixture was then heated under refluxing conditions for 45 h. After cooling to room temperature, cannula filtration yielded a bright yellow solution containing the light and airsensitive product. Removal of volatiles and subsequent drying *in vacuo* afforded dibromoborylcymantrene in 64% yield. Previous literature reports provided confirmation of the successful synthesis in the form of <sup>1</sup>H and <sup>11</sup>B NMR.<sup>4</sup>

## Preparation of (R,R) and (S,S)-Stilbenediol (1,2-diphenyl-1,2-ethanediol)

The syntheses of both (R,R) and (S,S)-(CHPhOH)<sub>2</sub> were carried out following the method of Sharpless *et. al.*<sup>8</sup> A solution of potassium ferricyanide (33 g, 0.1 mol) and potassium carbonate (14 g, 0.1 mol) in water (160 cm<sup>3</sup>) was added to a solution of *trans*-stilbene (6 g, 33 mmol), methane sulphonamide (3.16 g, 33 mmol) and either (DHQ)<sub>2</sub>PHAL [for (R,R) enantiomer] or (DHQD)<sub>2</sub>PHAL [for (S,S) enantiomer] (0.01 equivalents, 0.33 mmol) in 2-methyl-2-propanol (160 cm<sup>3</sup>) and stirred vigorously.

Potassium osmate (VI) dihydrate (0.049 g, 0.13 mmol) was then added to the reaction vessel, and the contents stirred vigorously for 48 h. To the now yellow reaction mixture sodium sulphite (4.2 g, 33 mmol) was added, followed by dilution with ethyl acetate (180 cm<sup>3</sup>). The organic layer was then washed with dilute  $H_2SO_4$  (20 cm<sup>3</sup>, 1 M), followed by a solution of NaHCO<sub>3</sub> (30 cm<sup>3</sup>, 1 M in  $H_2O$ ) and finally water (50 cm<sup>3</sup>). Subsequent drying of the organic phase over MgSO<sub>4</sub>, filtration, and removal of solvent on a rotor evaporator yielded a white crystalline solid, recrystallised from hot toluene in 71% yield. Characterisation in the form of <sup>1</sup>H and <sup>13</sup>C NMR were in agreement with previous literature publications.<sup>9</sup>

## Preparation of Napthalenediol [1-(2-napthyl)-1,2-ethanediol]

The method of Sharpless *et. al.*<sup>8</sup> was again utilised for the synthesis of the napthalenediol precursor. A solution of potassium ferricyanide (32 g, 0.1 mol) and potassium carbonate (13.4 g, 0.1 mol) in water (160 cm<sup>3</sup>) was added to a solution of 2vinylnapthalene (5 g, 32.4 mmol) and (DHQD)<sub>2</sub>PHAL [*(S,S)* enantiomer] (0.253g, 0.33 mmol) in 2-methyl-2-propanol (160 cm<sup>3</sup>) with vigorous stirring. Potassium osmate (VI) dihydrate (0.047 g, 0.13 mmol) was then added to the reaction vessel, and the contents stirred vigorously for 48 h. To the reaction mixture was added sodium sulphite (4.2 g, 33 mmol), followed by dilution with ethyl acetate (180 cm<sup>3</sup>). The organic layer was then washed with dilute H<sub>2</sub>SO<sub>4</sub> (20 cm<sup>3</sup>, 1 M), followed by NaHCO<sub>3</sub> solution (30 cm<sup>3</sup>, 1 M in H<sub>2</sub>O) and finally water (50 cm<sup>3</sup>). Subsequent drying of the organic phase over MgSO<sub>4</sub>, filtration, and the removal of solvent on a rotor evaporator yielded a white crystalline solid, recrystallised from hot toluene in 65% yield. <sup>1</sup>H NMR was employed for characterisation, which was in agreement with earlier reports.<sup>9, 10</sup>

#### Preparation of tetrahydroxybenzene

1,2,4,5-Tetrahydroxybenzene was synthesised in essentially quantitative yield according to the method of Hegedus and co-workers.<sup>11</sup> To a suspension of dihydroxy*para*-quinone (10 g, 0.07 mol) in conc. HCl (200 cm<sup>3</sup>) was added slowly granular tin (10 g), and the mixture heated at reflux for 2 h. Filtration whilst hot and subsequent cooling to 0°C yielded off-white crystals, recrystallised from hot THF to form the pure compound as white crystals. IR and <sup>1</sup>H NMR spectra were in accordance with previous literature reports.<sup>11</sup>

## Preparation of 1, 2, 4, 5-(Me<sub>3</sub>SiO)<sub>4</sub>C<sub>6</sub>H<sub>2</sub>

Minor modification of the procedure as reported by Calder<sup>12</sup> was employed for the synthesis of the trimethylsilyl derivative of tetrahydroxybenzene. To a suspension of tetrahydroxybenzene (5 g, 35.2 mmol) in toluene (40 cm<sup>3</sup>) was added *via* syringe triethylamine (four equivalents, 19.6 cm<sup>3</sup>, 0.14 mol) and chlorotrimethylsilane (four equivalents, 17.9 cm<sup>3</sup>, 0.14 mol). After stirring at room temperature, the reaction mixture was filtered *via* cannula, the white (Et<sub>3</sub>NH)Cl precipitate washed with toluene (2 x 15 cm<sup>3</sup>) and the combined washings reduced to dryness *in vacuo*. The resultant solid was extracted into hexanes, filtered and concentrated prior to recrystallisation at  $-30^{\circ}$ C. <sup>1</sup>H and <sup>13</sup>C NMR spectra in agreement with those previously reported confirmed the formation of 1,2,4,5-(Me<sub>3</sub>SiO)<sub>4</sub>C<sub>6</sub>H<sub>2</sub>.<sup>12</sup>

## Preparation of Ferroceneboronic acid, FcB(OH)<sub>2</sub>

Ferroceneboronic acid was prepared by minor adjustment of the method reported by Floris and Illuminati.<sup>13</sup> BBr<sub>3</sub> (4 cm<sup>3</sup>, 10.6 g, 42.3 mmol) in hexane (30 cm<sup>3</sup>) was slowly added to a slurried mixture of ferrocene (27.5 g, 0.15 mol) and AlCl<sub>3</sub> (6.58 g,

0.05 mol) in hexane (200 cm<sup>3</sup>). The mixture was then heated at reflux for 4 h, after which cannula filtration yielded a dark red solution. NaOH (100 cm<sup>3</sup>, 15 % aq. solution) was added dropwise to the filtrate while under argon and an orange precipitate was deposited in the aqueous layer.  $H_2SO_4$  (90 cm<sup>3</sup>, 10 % aq. solution) was then added dropwise to neutralise any excess NaOH and the hexane layer removed by careful decantation. The orange precipitate within the aqueous layer was extracted with ether (3 x 50 cm<sup>3</sup>), and the solvent removed on a rotary evaporator. The crude solid was then washed repeatedly with petroleum ether (40-60°C) until the washings remained colourless, drying *in vacuo* and recrystallisation from ether/hexane afforded the pure compound in 33% yield. The <sup>1</sup>H NMR data reported by Floris and Illuminati<sup>13</sup> were in agreement with that observed.

#### Preparation of (Me<sub>3</sub>SiOCH<sub>2</sub>CH<sub>2</sub>)<sub>2</sub>NMe

(Me<sub>3</sub>SiOCH<sub>2</sub>CH<sub>2</sub>)<sub>2</sub>NMe was synthesised according to the method of Aldridge *et. al.*<sup>14</sup> *N*-Methyldiethanolamine (10 cm<sup>3</sup>, 87 mmol) was dissolved in toluene (80 cm<sup>3</sup>) and sequentially triethylamine (49 cm<sup>3</sup>, 0.35 mol) and chlorotrimethylsilane (45 cm<sup>3</sup>, 0.35 mol) added *via* syringe at room temperature. After 24 h of stirring, the toluene supernatent was filtered *via* cannula, and the white precipitate of (Et<sub>3</sub>NH)Cl washed with further aliquots of toluene (2 x 25 cm<sup>3</sup>), combining the washings with the initial filtrate. After removal of volatiles under reduced pressure, the product was isolated as an orange/yellow liquid in 73% yield. <sup>1</sup>H and <sup>13</sup>C NMR indicated that the compound was >99% pure by comparison with data reported previously.<sup>14</sup> No further purification was therefore attempted.

## Preparation of 1-Piperidyl-2,3-propanediol C<sub>5</sub>H<sub>10</sub>N-CH<sub>2</sub>CH(OH)CH(OH)

Piperidine (11.6 cm<sup>3</sup>, 0.12 mol) was syringed into a solution of racemic glycidol (10 cm<sup>3</sup>, 0.15 mol) in ethanol (100cm<sup>3</sup>). The reaction flask was then sealed and the mixture stirred vigorously for 5 days. Filtration and removal of volatiles *in vacuo* yielded a gloopy colourless liquid which on cooling to  $-30^{\circ}$ C solidified to give a white solid in 77% yield. At this point <sup>1</sup>H and <sup>13</sup>C-NMR showed the product to be pure, hence further purification was not carried out. <sup>1</sup>H-NMR (CDCl<sub>3</sub>, 400MHz, 20°C):  $\delta$  1.38 [2H, m, CH<sub>2</sub> of piperidyl], 1.51 [4H, m, CH<sub>2</sub> of piperidyl], 2.26 [2H, m, N-CH<sub>2</sub> of piperidyl], 2.29 [1H, br, CH<sub>2</sub>OH], 2.44 [2H, m, N-CH<sub>2</sub> of piperidyl], 2.51 [1H, br, CHOH], 3.42 [2H, m, CH<sub>2</sub>OH], 3.64 [2H, m, NCH<sub>2</sub>], 3.74 [1H, m, CHOH]. <sup>13</sup>C{<sup>1</sup>H}-NMR (CDCl<sub>3</sub>, 300MHz, 20°C):  $\delta$  24.25 [CH<sub>2</sub> of piperidyl], 26.19 [CH<sub>2</sub> of piperidyl], 54.97 [CH<sub>2</sub> of piperidyl], 61.17 [CH<sub>2</sub>OH], 65.09 [NCH<sub>2</sub>], 66.66 [CHOH].

## Preparation of ["Bu<sub>4</sub>N][PF<sub>6</sub>] electrolyte

KPF<sub>6</sub> (20 g, 0.12 mol) in H<sub>2</sub>O (200 cm<sup>3</sup>) was added to an aqueous solution of ["Bu<sub>4</sub>N]Br. The resulting white precipitate was filtered (Buchner) and air-dried on the filter paper prior to recrystallisation from hot ethanol (~300 cm<sup>3</sup>). This recrystallisation was repeated four times in total, filtering the hot solution each time, and finally drying *in vacuo* (yield 70%).

## 2.4 References for Chapter Two

- D.F. Shriver and M. A. Drezdzon, *The Manipulation of Air-Sensitive Compounds*, 2<sup>nd</sup> edn., Wiley-Interscience, New York, 1986.
- 2. R. E. Dodd and P. L. Robinson, *Experimental Inorganic Chemistry*, Elsevier, 1954.
- 3. Saffron Scientific Equipment Ltd., glove box operation manual.
- 4. T. Renk, W. Ruf, W. Siebert, J. Organomet. Chem., 1976, 120, 1-25.
- 5. B. Wrackmeyer, U. Dörfler, M. Herberhold, Z. Naturforsch., Teil B, 1993, 48, 121.
- 6. A. Appel, H. Nöth, M. Schmidt, Chem. Ber., 1995, 128, 621.
- 7. W. Ruf, T. Renk, W. Siebert, Z. Naturforsch., 1976, 31b, 1028.
- 8. K. B. Sharpless, Chem. Rev., 1994, 94, 2483.
- C. Döbler, G.M. Mehltretter, U. Sundermeier, M. Beller, J. Am. Chem. Soc., 2000, 122, 10289.
- 10. F. J. Moreno-Dorado, F. M. Guerra, M. J. Ortega, E. Zubia, Tetrahedron: Asymmetry, 2003, 14, 503.
- P. R. Weider, L. S. Hegedus, H. Asada, S. V. D'Andreq, J. Org. Chem., 1985, 50, 4276.
- S. Aldridge, R. J. Calder, A. Rossin, A. A. Dickinson, D. J. Willock, C. Jones,
   D. J. Evans, J. W. Steed, M. E. Light, S. J. Coles, M. B. Hursthouse, J. Chem. Soc., Dalton Trans., 2002, 2020.
- 13. B. Floris, G. Illuminati, J. Organomet. Chem., 1978, 150, 101.
- S. Aldridge, R. J. Calder, D. L. Coombs, C. Jones, J. W. Steed, S. Coles, M. B. Hursthouse, New J. Chem., 2002, 26, 677.
# **Chapter Three**

# The Synthesis and Characterisation of Mono- and Bifunctional Boron-Containing Lewis Acids

## 3.1 Introduction

Metallocene and half-metallocene systems bearing boron substituted cyclopentadienyl ligands have attracted much attention over recent years. The interest in such compounds has manifested itself within the literature,<sup>1</sup> to the extent that the complexes featuring borate-substituted metallocene borvl spread of or cyclopentadienyl ligands have been reported for most of the transition series, with the exception of groups 3, 10, 11 and 12. In part, this widespread interest stems from potential applications in anion recognition and molecular sensing,<sup>2</sup> and in the case of group 4, in olefin polymerisation catalysis.<sup>3,4</sup> In particular, the stable 18 electron sandwich complexes containing group 8 metals have been subject to the most rigorous synthetic investigation in this field, and as a result are by far the most numerous.

With reference to the literature, it appears that the preparation of metallocene systems featuring pendant boryl functions can be classified into two main approaches: (i) introduction of the boron moiety to an existing metal-cyclopentadienyl fragment, and (ii) reaction of a transition metal precursor (e.g. halide/alkyl or amide), with a cyclopentadienyl ligand precursor containing a pendant boryl function. This second approach has been adopted by a number of groups. In particular, Shapiro and co-workers<sup>5,6</sup> have probed the reaction of neutral boryl-Cp ligand precursors with transition metal halides to form *ansa*-bridged species (*e.g.* compound I, Scheme 3.1), and investigated their catalytic properties for olefin polymerisation. Alternatively, the reaction of an alkali metal salt of an *anionic* boryl-cyclopentadienide ligand precursor with an appropriate transition metal halide can be employed, as shown by Herberich

et. al.<sup>7,8</sup> The resulting cobaltocene derivative (Scheme 3.1, II), can be oxidised to the corresponding cobaltocenium complex which has been shown to bind anions such as chloride and hydroxide. Both examples are highlighted by Scheme 3.1.



Scheme 3.1 Boron substituted metallocenes synthesised from pre-assembled borylcyclopentadienyl ligands.

The former and less widely applicable synthetic approach involves direct borylation of an existing metallocene,<sup>9-11</sup> either directly or *via* initial metallation of the Cp ring, with for example, a lithium<sup>12</sup> or tin substituent<sup>13</sup> (Scheme 3.2). Siebert *et. al.* have demonstrated that boron halides, and boron tribromide in particular, bring about electrophilic borylation of ferrocene to give both the *mono-* and *bis-* dihaloborylferrocenes (Scheme 3.2, **III**).<sup>10,11</sup> Similar chemistry was carried out by the same group on cymantrene systems; reaction with boron triiodide or boron tribromide yielded the respective dihaloborylcymantrenes.<sup>10,11</sup> Later work carried out by Appel, Nöth and Schmidt<sup>14</sup> extended this chemistry to report the synthesis of the *tris-* and *tetrakis-*dihaloboryl derivatives of ferrocene, ruthenocene and osmocene using neat BBr<sub>3</sub>. Hence, not only is it possible to incorporate up to four boryl groups in the

metallocene system, but further modification is also accessible from boron centred substitution of the halogen atoms.<sup>15,16</sup>



Scheme 3.2 Direct borylation of metallocene precursors with boron halides.

As mentioned previously, the boron containing moiety can also be introduced by reaction of the boron halide with a metallated cyclopentadienyl ring. Manners and colleagues<sup>13</sup> exploited this particular approach using the tin-containing ferrocenophane **IV** (Scheme 3.2), reaction of which with one equivalent of boron trichloride provided a means of introducing one dichloroboryl unit to the metallocene.

The use of lithiated-metallocene precursors for borylation chemistry has been demonstrated, for example, by Braunschweig *et. al.*, in preparing boron *ansa*-bridged species such as **VII** (Figure 3.1), *via* the salt elimination reaction between dilithioferrocene and an amino-substituted boron dihalide.<sup>12</sup> Prior to this report, Braunschweig and co-workers had synthesised a borate-functionalised tungstenocene trihydride<sup>9</sup> (Figure 3.1, **VI**), thereby demonstrating that direct borylation methods can be applied to groups other than 8.



Although this method of preparation is undoubtedly a more convenient route, it remains largely limited in application to the stable, eighteen-electron sandwich compounds of group 8. As a result, the alternative route of incorporating preassembled boryl or borate cyclopentadienyl ligands into synthetic strategies has found its place in forming analogous systems of the other transition metal groups. In particular, the method has found important application in the synthesis of group 4 single component and *ansa*-bridged catalysts.

## 3.1.1 Aims of the present research

Making use of the direct borylation chemistry reported by Siebert and coworkers,<sup>10,11</sup> it was decided to further derivatize these *mono-* and *bis*dihaloborylferrocene and dihaloborylcymantrene systems to form a range of *mono*and *bis-*boronate esters based on the respective metallocene framework (Scheme 3.3). Boronic acids of ferrocene have been known for over forty years,<sup>17</sup> however, boronate esters have been much less investigated. The choice of ferrocene as the backbone was due to the synthetic ease of borylation, and the ease and scope of further derivatization at boron. This allows tuning of the Lewis acidity at the boron centres, together with the possibility of ready modification to include chiral backbones for potentially enantioselective binding agents. In addition, such systems offer a robust

and stable structure, combined with ready spectroscopic and electrochemical investigation. It was also decided to investigate analogous boryl-substituted derivatives of cymantrene, in which case it might prove possible to monitor anion binding processes *via* infrared spectroscopy.



Scheme 3.3 Ferrocene and Cymantrene based boronic esters synthesised from direct borylation of cyclopentadienyl ligands and subsequent salt elimination chemistry.

## 3.2 Experimental

### Preparation of Bidentate bis(boronate) Lewis acids 1a, 2a, 3a, 4a, 5a

A common method was employed in each case. The required diol (typically 2.3 g, 10.74 mmol for 1a) was dried *in vacuo*, dissolved in toluene (*ca*. 50 ml), and the resulting solution cooled to  $-78^{\circ}$ C. *n*-Butyllithium (2 equivalents of a 1.6 M in hexanes) were added dropwise by syringe. The resulting slurry (1a, 2a, 3a, 4a) or yellow solution (5a) was warmed to room temperature and stirred for a further 2h. A solution of 1,1'-*bis*(dibromoboryl)ferrocene (0.5 equivalents) in toluene was transferred *via* cannula to the dilithiate mixture at room temperature, and stirred for 24 h. Cannula filtration of the cloudy reaction mixture yielded a clear orange filtrate, and off-white residue. Removal of the toluene solvent *in vacuo* afforded an oily

orange residue, which was subjected to further continuous pumping. Hexanes or petroleum ether were used to wash the solid, combining the washings each time by cannula filtration until the washings were colourless. Finally, recrystallisation from the same solvent at  $-30^{\circ}$ C yielded the respective bidentate Lewis acid in a spectroscopically and analytically pure form.

# Spectroscopic data for 1a

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  4.39 [m, 2H, C<sub>3</sub>H<sub>4</sub>], 4.44 [m, 2H, C<sub>3</sub>H<sub>4</sub>], 4.88 [m, 2H, C<sub>3</sub>H<sub>4</sub>], 4.99 [m, 2H, C<sub>3</sub>H<sub>4</sub>], 5.30 [s, 4H, CH of chelate], 7.04-7.26 [m, 20H, C<sub>6</sub>H<sub>5</sub>]; accidental degeneracy of two of the four unique cyclopentadienyl hydrogens is observed in CDCl<sub>3</sub>: ([D]chloroform, 20 °C),  $\delta$  4.55 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 4.61 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 4.71 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 5.28 [s, 4H, CH of chelate], 7.37 [m, 20H, C<sub>6</sub>H<sub>5</sub>]; <sup>13</sup>C NMR ([D]chloroform, 20 °C),  $\delta$  72.9, 73.5, 75.1, 75.5 [CH of C<sub>3</sub>H<sub>4</sub>], 86.9 [CH of chelate], 126.2, 128.4, 128.8 [aromatic CH], 140.1 [aromatic quaternary]; <sup>11</sup>B NMR ([D]chloroform, 20 °C),  $\delta$  34.0 (br); IR (KBr disc, cm<sup>-1</sup>),  $\nu$  = 3030 w, 2912 w, 1482 st, 1455 md, 1382 st, 1328 st, 1301 md, 1215 w, 1177 md, 1027 w, 980 md, 762 md, 700 st, 682 st; UV/Vis (chloroform):  $\lambda_{max}$  ( $\varepsilon$ ) 450 nm,  $\varepsilon$  = 209 cm<sup>-1</sup> mol<sup>-1</sup> dm<sup>3</sup>; MS(EI): M<sup>+</sup> = 630 (100%), exact mass (calc.) *m/z* 630.1836, (obs.) 630.1834; Elemental analysis: calcd (%) for C<sub>38</sub>H<sub>32</sub>B<sub>2</sub>FeO<sub>4</sub>: C 72.43, H 5.08; found: C 72.61, H 5.13%.

# Spectroscopic data for 2a

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  4.13 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.67 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 6.77-6.96 [m, 8H, C<sub>6</sub>H<sub>4</sub>]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  73.5, 74.6 [CH of C<sub>5</sub>H<sub>4</sub>], 112.3, 122.4 [aromatic CH], 148.8 [aromatic quaternary]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  34.0 (br); <sup>1</sup>H NMR ([D]chloroform, 20 °C),  $\delta$  4.53 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.68 [m, 4H,

 $C_5H_4$ ], 7.04-7.11 [m, 8H,  $C_6H_4$ ]; IR (KBr disc, cm<sup>-1</sup>), v = 3313 md, 1501 md, 1470 st, 1383 md, 1316 st, 1239 st, 1106 md, 896 w, 737 md, 681 w; UV/Vis (chloroform):  $\lambda_{max}$  ( $\epsilon$ ) 441 nm; MS(EI): M<sup>+</sup> = 422 (100%), exact mass (calc.) *m/z* 422.0579, (obs.) 422.0575.

# Spectroscopic data for 3a

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  1.31 [s, 18H, 'Bu], 1.57 [s, 18H, 'Bu], 4.23 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.68 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 7.22-7.28 [m, 4H, C<sub>6</sub>H<sub>2</sub>]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  29.8, 31.7, 34.4, 34.8 [aliphatic *tert*-butyl], 73.5, 74.6 [CH of C<sub>5</sub>H<sub>4</sub>], 107.9, 116.2 [aromatic CH], 134.6, 144.6, 145.5, 149.1 [aromatic quaternary]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  34.0 (br); <sup>1</sup>H NMR ([D]chloroform, 20 °C),  $\delta$  1.37 [s, 18H, 'Bu], 1.49 [s, 18H, 'Bu], 4.47 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.66 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 7.06-7.17 [m, 4H, C<sub>6</sub>H<sub>2</sub>]; IR (KBr disc, cm<sup>-1</sup>), v = 2954 st, 2868 md, 1628 w, 1602 w, 1484 st, 1413 st, 1382 st, 1314 st, 1263 st, 1241 st, 1198 md, 1118 st, 1026 st, 977 st, 893 md, 858 md, 815 md, 693 md; UV/Vis (chloroform):  $\lambda_{max}$  ( $\varepsilon$ ) 444nm; MS(EI): M<sup>+</sup> = 646 (48%), exact mass (calc.) *m/z* 646.3088, (obs.) 646.3094.

# Spectroscopic data for 4a

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  3.47 [s, 6H, OCH<sub>3</sub>], 4.10 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.64 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 6.37-6.39 [m, 2H, C<sub>6</sub>H<sub>3</sub>], 6.76-6.78 [m, 4H, C<sub>6</sub>H<sub>3</sub>]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  55.8 [OCH<sub>3</sub>], 73.5, 74.6 [CH of C<sub>5</sub>H<sub>4</sub>], 105.4, 107.6, 122.5 [aromatic CH], 146.1, 150.4 [aromatic quaternary]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  34.0 (br); <sup>1</sup>H NMR ([D]chloroform, 20 °C),  $\delta$  3.97 [s, 6H, OCH<sub>3</sub>], 4.51 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.73 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 6.65-6.69 [m, 2H, C<sub>6</sub>H<sub>3</sub>], 6.77-6.80 [m, 2H, C<sub>6</sub>H<sub>3</sub>], 6.96-6.99 [m, 2H, C<sub>6</sub>H<sub>3</sub>]; IR (KBr disc, cm<sup>-1</sup>), v = 3093 md, 2996 md, 2960 md, 2832 w,

1634 st, 1506 st, 1449 st, 1316 st, 1075 st, 1029 md, 896 md, 819 w, 763 md, 722 md, 686 md, 522 w, 487 w; UV/Vis (chloroform):  $\lambda_{max}$  ( $\varepsilon$ ) 449 nm; MS(EI): M<sup>+</sup> = 482 (34%), exact mass (calc.) *m/z* 482.0795, (obs.) 482.0802.

# Spectroscopic data for 5a

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  3.96 [m, 1H, CH<sub>2</sub> of chelate], 4.27 [m, 1H, CH<sub>2</sub> of chelate], 4.40 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.87 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 5.38 [m, 1H, CH of chelate], 7.23-7.26 [m, 6H, C<sub>10</sub>H<sub>7</sub>], 7.58-7.74 [m, 8H, C<sub>10</sub>H<sub>7</sub>]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$ 72.9 [CH of C<sub>5</sub>H<sub>4</sub>], 73.2 [CH<sub>2</sub> of chelate], 75.0 [CH of C<sub>5</sub>H<sub>4</sub>], 75.3 [CH of C<sub>5</sub>H<sub>4</sub>], 78.9 [CH of chelate], 123.6, 125.0, 126.0, 126.3, 128.7 [aromatic CH], 133.4, 133.5, 138.9 [aromatic quaternary]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  33.2 (br); <sup>1</sup>H NMR ([D]chloroform, 20 °C),  $\delta$  4.22 [m, 2H, CH<sub>2</sub> of chelate], 4.51 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.59 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.76 [m, 2H, CH<sub>2</sub> of chelate], 5.70 [m, 2H, CH of chelate], 7.46-7.49 [m, 6H, C<sub>10</sub>H<sub>7</sub>], 7.81-7.88 [m, 8H, C<sub>10</sub>H<sub>7</sub>]; IR (KBr disc, cm<sup>-1</sup>), v = 2956 w, 2895 w, 1579 w, 1488 st, 1473 st, 1378 md, 1322 md, 1292 w, 1132 st, 1046 w, 996 w, 825 w; UV/Vis (chloroform):  $\lambda_{max}$  ( $\varepsilon$ ) 447 nm; MS(EI): M<sup>+</sup> = 578 (18%), exact mass (calc.) *m/z* 578.1518, (obs.) 578.1521.

## Alternative synthesis of bidentate bis(boronate) Lewis acid 5a from $fc[B(OH)_2]_2$

1,1'-Ferrocenediboronic acid (1 g, 3.66 mmol) and (S)-1-napthyl-ethane-1,2-diol (1.38 g, 7.31 mmol) were dissolved in acetone and placed in a sealed tube. The mixture was then stirred for 96 h at 75°C. Removal of solvent *in vacuo* and subsequent column chromatography on silica eluted with chloroform yielded samples of **5a** with identical spectroscopic properties ( $^{11}B$ ,  $^{1}H$  and  $^{13}C$  NMR) to that

synthesised *via* the method outlined in scheme 3.3. The yield of 18 % appears to be limited by the low purity of commercially available 1,1'-ferrocenediboronic acid.

## Preparation of monodentate mono(boronate) Lewis acids 1b, 2b

The monodentate derivatives were synthesised from dibromoborylferrocene in a manner analogous to that described above for the bidentate Lewis acids. However, in this case the diol dilithiate and dibromoborylferrocene were reacted in a 1:1 stoichiometry, rather than 2:1.

# Spectroscopic data for 1b

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  4.17 [s, 5H, C<sub>3</sub>H<sub>5</sub>], 4.29 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 4.76 [m, 1H, C<sub>3</sub>H<sub>4</sub>], 4.80 [m, 1H, C<sub>5</sub>H<sub>4</sub>], 5.25 [s, 2H, CH of chelate], 7.10-7.28 [m, 10H, C<sub>6</sub>H<sub>5</sub>]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  68.8 [CH of C<sub>3</sub>H<sub>5</sub>], 72.7 [CH of C<sub>5</sub>H<sub>4</sub>], 74.3, 74.4 [CH of C<sub>5</sub>H<sub>4</sub>], 86.7 [CH of chelate], 126.1 [aromatic CH], 128.8 [aromatic CH], 141.1 [aromatic quaternary]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  34.1 (br); <sup>1</sup>H NMR ([D]chloroform, 20 °C),  $\delta$  4.25 [s, 5H, CH of C<sub>3</sub>H<sub>5</sub>], 4.49 [s, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.59 [m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 5.29 [s, 2H, CH of chelate], 7.37-7.42 [m, 10H, C<sub>6</sub>H<sub>5</sub>]; IR (KBr disc, cm<sup>-1</sup>), v = 3085 w, 2918 w, 1501 md, 1481 st, 1451 md, 1379 md, 1372 w, 1321 st, 1298 w, 1269 md, 1205 w, 1173 md, 1128 st, 1105 md, 1036 md, 998 md, 826 md, 764md, 701 md, 685 w; UV/Vis (chloroform):  $\lambda_{max}$  ( $\varepsilon$ ) 448 nm,  $\varepsilon$  = 179 cm<sup>-1</sup> mol<sup>-1</sup> dm<sup>3</sup>; MS(EI): M<sup>+</sup> = 408 (100%), exact mass (calc.) *m/z* 408.0984, (obs.) 408.0985.

#### Spectroscopic data for 2b

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  3.95 [s, 5H, C<sub>5</sub>H<sub>5</sub>], 4.28 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 4.78 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 6.87-7.89 [m, 2H, C<sub>6</sub>H<sub>4</sub>], 7.16-7.19 [m, 2H, C<sub>6</sub>H<sub>4</sub>]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  68.8 [CH of C<sub>5</sub>H<sub>5</sub>], 73.2 [CH of C<sub>5</sub>H<sub>4</sub>], 73.9 [CH of C<sub>5</sub>H<sub>4</sub>], 112.4 [aromatic CH], 122.6 [aromatic CH]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  34.3 (br); <sup>1</sup>H NMR ([D]chloroform, 20 °C),  $\delta$  4.15 [s, 5H, CH of C<sub>5</sub>H<sub>5</sub>], 4.56 [m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.68 [m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 7.08-7.12 [m, 2H, C<sub>6</sub>H<sub>4</sub>], 7.25-7.27 [m, 2H, C<sub>6</sub>H<sub>4</sub>]; IR (KBr disc, cm<sup>-1</sup>), v = 3304 w, 1506 md, 1469 st, 1382 md, 1312 st, 1235 st, 1112 md, 1025 w, 1002 w, 894 w, 810 md, 751 st; UV/Vis (chloroform):  $\lambda_{max}$  ( $\varepsilon$ ) 434 nm; MS(EI): M<sup>+</sup> = 304 (100%), exact mass (calc.) *m/z* 304.0358, (obs.) 304.0362.

# Preparation of bridged bis(ferrocenyl) derivative FcBO<sub>2</sub>C<sub>6</sub>H<sub>2</sub>O<sub>2</sub>BFc, 6

To a stirred solution of dibromoborylferrocene (1 g, 2.81 mmol) in toluene (60 cm<sup>3</sup>) was added dropwise *via* cannula a solution of 1,2,4,5-(Me<sub>3</sub>SiO)<sub>4</sub>C<sub>6</sub>H<sub>2</sub> in toluene (60 cm<sup>3</sup>). The resultant mixture was then heated to 80°C for 1 week, during which time the reaction mixture had become orange-yellow in colour. <sup>11</sup>B NMR of the reaction mixture at this point revealed the major product at  $\delta_B$  34. Subsequent filtration *via* cannula and removal of volatiles *in vacuo* yielded a yellowish solid, which was washed with dry hexane (40 cm<sup>3</sup>), filtered and dried *in vacuo*. The yellow-orange solid was extracted into a sufficient volume of warm toluene, filtered and cooled to -30°C resulting in precipitation of the pure compound, 19 % yield (unoptimised).

## Spectroscopic data for 6

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  3.93 [s, 10H, C<sub>5</sub>H<sub>5</sub>], 4.23 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.71 [m, 4H, C<sub>5</sub>H<sub>4</sub>], 6.94 [s, 2H, aromatic CH]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  68.8 [CH of C<sub>5</sub>H<sub>5</sub>], 73.2 [CH of C<sub>5</sub>H<sub>4</sub>], 73.8 [CH of C<sub>5</sub>H<sub>4</sub>], 98.0 [aromatic CH]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  34.2 (br); IR (KBr disc, cm<sup>-1</sup>), v = 2965 st, 1493 md, 1458 st, 1383 md, 1337 w, 1312 md, 1262 md, 1142 st, 1101 md, 1026 w, 901 w, 845 w, 810 w, 685 w; UV/Vis (chloroform):  $\lambda_{max}$  ( $\epsilon$ ) 439 nm; MS(EI): M<sup>+</sup> = 530 (84%), exact mass (calc.) *m/z* 530.0246, (obs.) 530.0255.

## Preparation of cymantrene-based boryl Lewis acids 7 and 8

*n*-Butyllithium (2 equivalents of a 1.6 M solution in hexanes) was added dropwise by syringe to a stirred solution of the vacuum dried diol in toluene (hydrobenzoin) or toluene/THF (50:50 mixture for catechol) at  $-78^{\circ}$ C. The resulting dilithiate slurry was stirred for a further 2h at room temperature. A toluene solution of dibromoborylcymantrene (1 equiv.) was transferred dropwise *via* cannula to the dilithiate slurry/solution. The reaction mixture was stirred for 24 h, followed by cannula filtration to remove the insoluble white precipitate and yield a pale yellow filtrate. Complete removal of solvent afforded the crude compound as a yellow oily residue, which was subsequently re-dissolved in hexanes (sparingly soluble), filtered by cannula and recrystallised from the same solvent at -30°C.

# Spectroscopic data for 7

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  4.03 [m, 1H, C<sub>5</sub>H<sub>4</sub>], 4.05 [m, 1H, C<sub>5</sub>H<sub>4</sub>], 4.94 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 5.12 [s, 2H, CH of chelate], 7.08-7.16 [m, 10H, C<sub>6</sub>H<sub>5</sub>]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  85.4 [CH of C<sub>5</sub>H<sub>4</sub>], 87.2 [CH of chelate], 91.8, 92.0 [CH of

C<sub>5</sub>H<sub>4</sub>], 125.9, 128.4, 128.8 [aromatic CH], 140.1 [aromatic quaternary], 224.6 [CO]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  31.0 (br); <sup>1</sup>H NMR ([D]chloroform, 20 °C),  $\delta$  4.94 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 5.26 [s, 2H, CH of chelate], 5.28 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 7.34-7.41 [m, 10H, C<sub>6</sub>H<sub>5</sub>]; IR (KBr disc, cm<sup>-1</sup>), v = 2028 st (CO symmetric), 1949 st (CO asymmetric); MS(EI): M<sup>+</sup> = 426 (35%), exact mass (calc.) *m/z* 426.0466, (obs.) 426.0465.

# Spectroscopic data for 8

<sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  3.97 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 4.87 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 6.71-6.80 [m, 2H, C<sub>6</sub>H<sub>4</sub>], 6.91-7.02 [m, 2H, C<sub>6</sub>H<sub>4</sub>]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  85.4 [CH of C<sub>5</sub>H<sub>4</sub>], 91.6 [CH of C<sub>5</sub>H<sub>4</sub>], 112.6, 124.1 [aromatic CH], 148.2 [aromatic quaternary]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 20 °C),  $\delta$  30.9 (br); <sup>1</sup>H NMR ([D]chloroform, 20 °C),  $\delta$  4.98 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 5.39 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 7.11-7.13 [m, 2H, C<sub>6</sub>H<sub>4</sub>], 7.24-7.27 [m, 2H, C<sub>6</sub>H<sub>4</sub>]; IR (KBr disc, cm<sup>-1</sup>),  $\nu$  = 2025 st (CO, symmetric), 1955 st br (CO, asymmetric); (solution in CDCl<sub>3</sub>, cm<sup>-1</sup>),  $\nu$  = 2028 st (CO, symmetric), 1959 st br (CO asymmetric); MS(EI): M<sup>+</sup> = 321 (39%), exact mass (calc.) *m/z* 321.9840, (obs.) 321.9844.

# 3.3 Results and discussion

# 3.3.1 Bis(boronate) ferrocene-based Lewis acids

*Bis*-boronic esters based on the ferrocene backbone (compounds 1a-5a) were successfully synthesised using direct metalloceneborylation chemistry,<sup>11,14</sup> followed by subsequent salt elimination reaction with the respective diol-dilithiate (Scheme 3.4). In all cases a yellow-orange solid was obtained with yields typically in the order of 20-45 % (unoptimised). With respect to air and moisture sensitivity, only compounds 1a and 5a were stable in air, whereas the catecholate-boronic ester and

substituted catecholate-boronic ester derivatives decomposed over a period of a few hours, unless kept under an inert atmosphere.



Scheme 3.4 Synthetic route to bidentate bis-borylferrocenes.

More specifically, spectroscopic investigation (<sup>1</sup>H and <sup>13</sup>C NMR) of the product formed from reaction of fc(BBr<sub>2</sub>)<sub>2</sub> with lithiated-(*R*,*R*) or (*S*,*S*)-stilbenediol (**1a**)<sup>18</sup> revealed inequivalence of all four CH groups of the cyclopentadiene rings, indicating the presence of the chiral diol substituents at boron. Examination of the <sup>11</sup>B NMR of **1a** indicated a single peak ( $\delta_B = 34.3$ ), indicating the presence of the boron in a single environment. Furthermore, the observed chemical shift is similar to that of 1,1'-ferrocenediboronic acid ( $\delta_B=30$ ),<sup>19</sup> and is entirely consistent with a three coordinate boron centre attached to two  $\pi$  oxygen donors and an aromatic ring system [*c.f.* PhB(OH)<sub>2</sub> at 28 ppm]. The inferences based on spectroscopic data are confirmed by an X-ray diffraction study. Cooling a solution of **1a** in benzene/petroleum ether (1:6) to -30°C for one week yielded single crystals suitable for X-ray diffraction, the structure of which is illustrated in Figure 3.2. Table 3.1 lists

selected bond lengths and angles relating to the structure of 1a, which under these conditions was obtained as the benzene solvate (1:2).



**Figure 3.2** Molecular structure of  $Fe[\eta^5-C_5H_4B(OCHPh)_2]_2$ ,  $[1a\cdot 2(C_6H_6)]$ . ORTEP ellipsoids set at the 30% probability level; hydrogen atoms omitted for clarity.

Fe(1)-C(1)	2.047(4)	B(1)-C(1)	1.509(7)
O(1)-B(1)	1.367(5)	C(1)-C(2)	1.425(5)
O(2)-B(1)	1.386(6)	C(6)-C(7)	1.547(5)
B(1)-O(1)-C(6)	107.9(3)	C(2)-C(1)-C(5)	104.5(4)
B(1)-O(2)-C(7)	106.6(3)	C(2)-C(1)-B(1)	126.4(4)
O(1)-B(1)-O(2)	113.0(4)	C(5)-C(1)-B(1)	128.1(5)
O(1)-B(1)-C(1)	123.2(5)	C(4)-C(5)-C(1)	110.0(4)
O(2)-B(1)-C(1)	123.8(4)		
B(1)-Cp(centroid)-Cp(centroid)-B(2)		52.6(6)	

 Table 3.1
 Bond distances (Å) and angles (°) for 1a (as 1:2 benzene solvate).

The O-B-O angles in the solid state structure of **1a** are found to be  $112.7(5)^{\circ}$  and  $113.0(4)^{\circ}$ ; these are lower than for an idealised trigonal planar geometry due to the 5-membered heteroatom ring being of fixed geometry, which close the angles slightly. The sum of angles about boron is found to be  $360.1(3)^{\circ}$ , indicating that the boron centres are in a trigonal planar environment as expected from the NMR data. The intramolecular boron-boron distance [3.790(4) Å], is somewhat larger than the distance between the cyclopentadiene rings [3.304(5) Å], due to the fact that the boronic ester groups are not eclipsed, and are twisted slightly away from each other. Given this observed intramolecular B···B distance for a torsion angle of *ca*. 53°; the corresponding B···B distance in an eclipsed conformation is calculated to be *ca*. 2.87 Å. On the basis of idealistic B-F distances for B-F-B units (*e.g.* ~1.5Å in [F<sub>3</sub>B-F-BF<sub>3</sub>]<sup>- 21</sup>), this distance appears ideal for fluoride to bind in a chelating manner to both

boron centres, assuming an eclipsed geometry can be achieved by rotation about the Cp-Fe-Cp axis. The structure of **1a** also displays an unexpected conformation in which the torsion angle  $\Box$ B-Cp(centroid)-Cp(centroid)-B is only 52.6(6)°. On grounds of sterics, this angle might be expected to be considerably larger (i.e.  $\approx 180^{\circ}$ ). The solid state structures of some analogous systems have revealed a much greater torsion angle, in particular, the bis-boronic ester derivatives based on ethane-1,2-diol {fc[B(OCH<sub>2</sub>)<sub>2</sub>]<sub>2</sub>} and pinane-diol {fc[Bpinanediolate]<sub>2</sub>}<sup>20</sup> both exhibit torsion angles close to 180°.

The solid state structure indicates the presence of two molecules of benzene in the lattice, giving a 1:2 solvate of **1a** with benzene. This may be one reason why the torsion angle is unexpectedly low at  $52.6(6)^{\circ}$ . It is conceivable that the benzene rings interact to give a  $\pi$ -stacking interaction with the phenyl groups, thus bringing the boryl substituents into a more eclipsed orientation. In an attempt to explain this unexpected geometry, single crystals of **1a** were grown in the absence of benzene, by slow evaporation of solvent from a concentrated petroleum ether solution (to yield the unsolvated compound). Figure 3.3 shows the crystal structure of **1a** obtained; relevant bond lengths and angles are listed in Table 3.2.



Figure 3.3 Molecular structure of  $Fe[\eta^5-C_5H_4B(OCHPh)_2]_2$  (1a). ORTEP ellipsoids set at the 30% probability level; hydrogen atoms omitted for clarity.

Fe(1)-C(1)	2.038(2)	B(1)-O(2)	1.378(3)
Fe(1)-C(23)	2.031(2)	B(1)-O(1)	1.378(3)
C(5)-B(1)	1.538(4)	B(2)-O(4)	1.369(3)
C(24)-B(2)	1.533(4)	B(2)-O(3)	1.372(3)
C(1)-C(2)	1.416(4)	C(6)-C(7)	1.548(3)
B(1)-O(1)-C(6)	106.2(2)	O(1)-B(1)-C(5)	122.0(2)
B(1)-O(2)-C(7)	106.3(2)	O(4)-B(2)-C(24)	123.5(2)
B(2)-O(3)-C(26)	107.5(2)	O(3)-B(2)-C(24)	123.0(2)
B(2)-O(4)-C(25)	107.6(2)	C(23)-C(24)-B(2)	126.2(2)
O(1)-B(1)-O(2)	113.4(2)	C(2)-C(1)-C(5)	108.6(2)
O(3)-B(2)-O(4)	113.6(2)	C(23)-C(24)-C(20)	105.9(2)
O(2)-B(1)-C(5)	124.6(2)		
B(1)-Cp(centroid)-Cp(ce	entroid)-B(2)	54.7(4)	

 Table 3.2
 Bond distances (Å) and angles (°) for 1a (unsolvated).

In the absence of benzene as co-crystallite, compound **1a** adopts a similar orientation to that of the benzene/petroleum ether solvate. The torsion angle [at  $54.7(4)^{\circ}$ ] is essentially the same as that found for  $1a \cdot 2C_6H_6$ . It seems unlikely, therefore that the presence of benzene molecules in the solid state structure have any significant role in determining the conformational preference of the ferrocenyl-bis(boronate) molecules. In addition, the structure of the non-solvated species reveals no significant intermolecular contacts between the phenyl rings of the boryl substituents, i.e.  $\pi$ -stacking does not appear to be responsible for the torsion angle of ~50°. On steric grounds, an angle of ~180° would be expected to minimise repulsion

between boryl substituents as observed in the ethane-1,2-diol and pinane-diol bisboronic ester derivatives {fc[B(OCH<sub>2</sub>)<sub>2</sub>]<sub>2</sub>} and pinane-diol {fc[Bpinanediolate]<sub>2</sub>}.<sup>20</sup> However, the barrier to rotation is unlikely to be very high until significant eclipsing of the boryl units occurs, and it may be that a value of ~50° represents little increase in unfavourable steric contacts, while at the same time allowing better packing of molecules in the solid state.

Analogous syntheses were also performed for (i) catechol (ii) 3,5-di-tertbutylcatechol and (iii) 3-methoxycatechol, all of which form air sensitive compounds (Figure 3.4). In all cases, reaction of the dilithiate with 1,1'-bis-dibromoborylferrocene leads to the corresponding Lewis acid, as characterised by the various spectroscopic methods available. <sup>1</sup>H and <sup>13</sup>C NMR data for 2a, 3a and 4a each indicate single substitution at each of the Cp ligands, such that the CH components in the 2 positions are equivalent (adjacent to boron), as are those in the 3 position. Furthermore, the aromatic backbones of the catechol moieties are apparent and are consistent with the typical ortho-disubstituted signature. The <sup>11</sup>B NMR shifts of these compounds all coincide at a shift of  $\delta_{\rm B} \approx 34$ , characteristic of three coordinate boron, as observed for Mass spectrometry results for the various catechol-based compound 1a. borylferrocenes all display molecular ion peaks, further verified by accurate mass measurement. Finally, infrared and UV/Vis spectra are also as expected for these ferrocene-based sytems. Although crystal growth has proved unsuccessful, it appears logical that the spectroscopic data here described is sufficient evidence to assign the formulations as depicted in Figure 3.4.





Figure 3.4 The proposed formulations of catechol-substituted bis-borylferrocenes.

A bis-borylferrocene system possessing a napthalene-substituted boronic ester function (**5a**) was also synthesised utilising the same procedure. Hence, following preparation of the napthalene-diol *via* Sharpless chemistry,<sup>22</sup> subsequent lithiation and reaction with  $fc(BBr_2)_2$  formed the orange air-stable Lewis acid **5a** in *ca*. 26 % yield. Attempts to grow single crystals of **5a** *via* methods such as solvent evaporation were ineffective. However, the <sup>11</sup>B NMR shift at  $\delta_B$  33 ppm, is similar to that of the structurally characterised **1a**,<sup>18</sup> analogous derivatives<sup>20</sup> and those with catecholatesubstituted boryl functions discussed previously. <sup>1</sup>H, <sup>13</sup>C NMR and mass spectrometry (including accurate mass determination) analyses are characteristic of the expected product and are in accordance with the structure portrayed in Scheme 3.5.

A second approach to the synthesis of compound **5**a was attempted using a method that has been extensively reported for the formation of cyclic esters of aryl boronic acids. In this case, the reaction of the commercially available 1,1'-ferrocene*bis*-boronic acid with the napthalene-diol precursor is found to yield samples of **5**a with identical spectroscopic properties (NMR) to those observed using the metathesis pathway. However, the yield (18 %) was low due to the poor quality of the commercially available 1,1'-ferrocenediboronic acid, fc[B(OH)<sub>2</sub>]<sub>2</sub>.





Scheme 3.5 Synthetic pathways to 5a.

An alternative synthetic strategy has been employed in the preparation of the bridged FcBO<sub>2</sub>C<sub>6</sub>H<sub>2</sub>O<sub>2</sub>BFc system 6, using a trimethylsilyl precursor in place of the usual lithiated alcohol. Thus, reaction of two equivalents of dibromoborylferrocene with (Me<sub>3</sub>SiO)<sub>4</sub>C<sub>6</sub>H<sub>2</sub> in toluene solution yields pure samples of the yellow air sensitive solid 6 in 19 % yield (unoptimised). <sup>1</sup>H, <sup>13</sup>C and <sup>11</sup>B NMR are in agreement with the expected product portrayed in Scheme 3.6, and mass spectrometry analyses (including exact mass measurements) confirm these inferences. The use of the trimethylsilyl precursor as a source of RO<sup>-</sup> eliminates the need for butyllithium treatment, and means that the reaction can conveniently be applied to diols/alcohols In forming the trimethylsilyl which are difficult to obtain as dry precursors. substituted species, the addition of a large excess of triethylamine and chlorotrimethylsilane moisture present to give serves to 'mop any up' hexamethyldisiloxane, removable in vacuo.

Furthermore, the replacement of <sup>*n*</sup>BuLi for  $Et_3N$  as the base has been exploited in the synthesis of the structurally characterised mono-substituted ferrocenyl system featuring a 1,3-propanediolate boronic ester,  $Fc[BO_2(CH_2)_3]$ , and the bi-substituted ferrocene systems with pinanediolate and ethanediolate boronic ester functions, again

characterised by XRD studies.<sup>20</sup> In conclusion, it appears that in total there are four synthetic routes which allow access to ferrocene systems substituted with boronic ester functionalities, all of which give similar results with regards to the purity of the products. However, the pathway that gives the best yield of product from a particular alcohol/diol starting material may depend on its physical form (dry/wet/solid/liquid), and therefore the ease of synthesis associated with each reaction.



Scheme 3.6 The alternative trimethylsilyl precursor route to compound 6.

## 3.3.2 Electrochemistry of bidentate bis-borylferrocenes

Cyclic voltammetry (CV) measurements were performed on compounds 1a-5a in an attempt to analyse the electronic effects of the respective boryl groups on the ferrocene backbone. These analyses were performed in dichloromethane or acetonitrile (depending on solubility), with ferrocene itself as a reference compound. The CV sweeps for compounds 1a and 2a are shown in Figures 3.5 and 3.6 respectively, and the observed oxidation potentials for all bis-boryl systems (1a-5a) are listed in Table 3.3. In all cases a reversible oxidation process is observed, however, the value of the oxidation potential itself is found to vary slightly according to the boryl-based substituents present.



Figure 3.6 Cyclic Voltammogram of 2a in MeCN with  $["Bu_4N]PF_6(0.1 \text{ M})$  as supporting electrolyte. Scan rate = 100 mV/s.

Compound	Solvent	Peak-Peak separation (Ep <sup>ox</sup> -Ep <sup>red</sup> ) (mV)	E <sub>1/2</sub> Relative to FcH (E <sub>1/2</sub> Ref.) (mV) <sup>a</sup>
1a	DCM	70	+206
<b>1</b> a	MeCN	80	+222
2a	MeCN	86	+92
<b>3</b> a	DCM	96	+294
<b>4</b> a	MeCN	86	+59
5a	DCM	75	+219

**Table 3.3** Electrochemical data of bidentate bis-borylferrocene systems 1a-5a with $[^{n}Bu_{4}N]PF_{6}(0.1 \text{ M})$  as supporting electrolyte.

<sup>a</sup> FcH vs S.C.E:  $E_{1/2} = 0.46$  V (DCM), 0.40 V(MeCN)

As illustrated by Figure 3.5, the cyclic voltammogram of 1a reveals a highly reversible oxidation process, presumably the result of the ferrocene/ferrocenium fragment redox couple. The highly reversible nature of this electrochemical process is indicated by its peak-peak separation (*i.e.* close to Nernstian behaviour, 59 mV). More importantly, however, is the position of the oxidation potential with respect to ferrocene itself. Oxidation of 1a in dichloromethane solution occurs at +206 mV, implying that compound 1a is itself more difficult to oxidise than ferrocene. Such behaviour is not surprising when the electron withdrawing effects of the boryl groups are considered. The boron atoms themselves are in these cases net-electron acceptors, thus withdrawing electron density from the aromatic system of the Cp ligands as well as the adjacent  $\pi$ -electron oxygen donors. As a result, the iron centre is to a small degree electron poor, and is hence more difficult to remove an electron, compared to ferrocene. Similar observations were made by the group of Piers, concerning the

electrochemistry of mono- and bis-borylated ferrocenes, possessing highly electron withdrawing  $-C_6F_5$  groups at boron.<sup>23</sup> The CV of **2a** (Figure 3.6) in acetonitrile solution shows similar results, in that oxidation occurs at a more positive potential relative to ferrocene, and again is characterised by a peak-peak separation consistent with a high degree of reversibility. The results for bis-boronate Lewis acids **3a**, **4a** and **5a** are similar to those for **1a** and **2a**.

In conclusion, it appears that the inherent electron deficiency associated with these three-coordinate boron species, and conjugation of the formally vacant boron p-orbital, enables electron donation from the  $\pi$ -orbitals of the cyclopentadienyl aromatic system, which results in a distinct anodic shift of the oxidation potential associated with the ferrocene moiety.

## 3.3.3 Mono(boronate) ferrocene-based Lewis acids

Once again employing the direct borylation methodology reported by Siebert *et. al.*,<sup>10</sup> it was possible to selectively introduce one boryl function to the ferrocene fragment, and in turn, further derivatize the Lewis acidic group as performed for the analogous bis(boronate) species. The orange coloured mono-functional Lewis acids **1b** and **2b** (Scheme 3.7) are accessible in yields of 64 % and 26 % (unoptimised) respectively, enabling a direct comparison with their bis-boryl analogues to be made. This would hopefully lead to a clearer understanding of the electronic effects associated with pendant three-coordinate boron-containing groups.



Scheme 3.7 Synthetic routes to mono-borylferrocenes 1b and 2b.

In the case of complex 1b, no sign of decomposition is seen when the compound is manipulated in air, even over prolonged periods. Spectroscopic characterisation in the form of <sup>1</sup>H and <sup>13</sup>C NMR confirmed the presence of a single boryl moiety. A singlet resonance due to the non-substituted Cp ligand was observed, together with the signals characteristic of mono-substituted Cp ligands. The <sup>11</sup>B NMR displays a broad singlet at  $\delta_B$  34.1, comparable with the bidentate analogue 1a and indicative of a Cp-pendant trigonal boron with oxygen substituents. Mass spectrometry data reveals both the expected molecular ion peak, and appropriate isotopic pattern. Slow evaporation of solvent from a concentrated solution of 1b in petroleum ether (40-60°C), enabled the growth of single orange-yellow crystals suitable for X-ray diffraction. The results of this analysis are illustrated as the solid state structure in Figure 3.7; selected geometric parameters are listed in Table 3.4.



**Figure 3.7** Molecular structure of  $(\eta^5 - C_5H_5)Fe[\eta^5 - C_5H_4B(OCHPh)_2]$  (1b). ORTEP ellipsoids set at the 30% probability level; hydrogen atoms omitted for clarity.

Fe(1)-C(1)	2.025(6)	C(11)-C(12)	1.562(6)
Fe(1)-C(10)	2.052(4)	C(1)-C(2)	1.400(10)
O(1)-B(1)	1.379(6)	C(9)-C(10)	1.434(7)
O(2)-B(1)	1.369(6)	O(2)-C(12)	1.438(5)
B(1)-C(10)	1.538(7)	O(1)-C(11)	1.434(5)
B(1)-O(1)-C(11)	108.6(3)	O(1)-C(11)-C(12)	103.7(3)
B(1)-O(1)-C(11) B(1)-O(2)-C(12)	108.6(3) 107.7(3)	O(1)-C(11)-C(12) O(2)-C(12)-C(11)	103.7(3) 104.7(3)
B(1)-O(1)-C(11) B(1)-O(2)-C(12) O(1)-B(1)-O(2)	108.6(3) 107.7(3) 113.1(4)	O(1)-C(11)-C(12) O(2)-C(12)-C(11) C(9)-C(10)-B(1)	103.7(3) 104.7(3) 125.9(4)
B(1)-O(1)-C(11) B(1)-O(2)-C(12) O(1)-B(1)-O(2) O(1)-B(1)-C(10)	108.6(3) 107.7(3) 113.1(4) 122.0(4)	O(1)-C(11)-C(12) O(2)-C(12)-C(11) C(9)-C(10)-B(1) C(6)-C(10)-B(1)	103.7(3) 104.7(3) 125.9(4) 127.6(5)
B(1)-O(1)-C(11) B(1)-O(2)-C(12) O(1)-B(1)-O(2) O(1)-B(1)-C(10) O(2)-B(1)-C(10)	108.6(3) 107.7(3) 113.1(4) 122.0(4) 124.8(4)	O(1)-C(11)-C(12) O(2)-C(12)-C(11) C(9)-C(10)-B(1) C(6)-C(10)-B(1) C(6)-C(7)-C(8)	103.7(3) 104.7(3) 125.9(4) 127.6(5) 108.7(5)

**Table 3.4** Bond distances (Å) and angles (°) for 1b.

The crystal structure of **1b** allows a comparison of bond lengths and angles to be made with that of **1a**, many of which are found to be similar between the two species. B-O bond lengths are within the expected region of ~1.37 Å, and are comparable with those found in the propane-diol cyclic boronate (Table 3.5).<sup>20</sup> In contrast, the O-B-O angle in the case of **1b** is a full 10° smaller [113.1(4)° c.f. 123.3(4)°] than found in the propane-diolate derivative. This is consistent with the smaller two-carbon bridge between oxygen atoms closing the angle (5-membered ring), compared to the larger three-carbon bridge in FcB[O<sub>2</sub>(CH<sub>2</sub>)<sub>3</sub>] (6 membered ring). The sum of angles [360.0(2)°] about the boron atom indicates the expected trigonal planar orientation. This planarity is not extended to the cyclopentadienyl ligand to which the boron is linked, since the boryl component is twisted out of the plane of the Cp ligand by an angle of 22.2(5)°. On the basis that orbitals of a similar symmetry can overlap to a greater extent, this twisting suggests that in the solid state; relatively more  $\pi$ -electron donation into the vacant  $p_z$  orbital at boron occurs from the adjacent oxygen atoms, rather than from the boryl-pendant Cp ligand.

B(1)-O(1)	1.364(5)	O(1)-C(1)cyclic boronate	1.446(4)
B(1)-O(2)	1.372(5)	O(2)-C(2)cyclic boronate	1.446(4)
C(Cp)-B(1)	1.543(6)		
O(1)-B(1)-O(2)	123.3(4)	B(1)-O(1)-C(1)cyclic boronate	120.2(3)
O(1)-B(1)-O(2) C(Cp)-B(1)-O(1)	123.3(4) 117.8(3)	B(1)-O(1)-C(1)cyclic boronate B(1)-O(2)-C(2)cyclic boronate	120.2(3) 119.1(3)

**Table 3.5** Bond distances (Å) and angles (°) for  $FcB[O_2(CH_2)_3]$ .<sup>20</sup>

The synthesis of the mono-borylferrocene system featuring a catecholate boronic ester function (2b) enables comparisons to be made with the bidentate derivative (2a) and the related stilbene-diol analogue (1b). Compound 2b is an orange-yellow crystalline solid, unstable under aerobic conditions but which can be manipulated and stored under inert atmosphere over long periods. Although yields of this compound are relatively poor, it can be isolated in high purity as indicated in the characterising data. <sup>1</sup>H and <sup>13</sup>C NMR spectra are in agreement with the proposed formulation (Scheme 3.6), showing clearly a single resonance due to the unsubstituted Cp ligand along with the expected signature for the boryl-substituted Cp (equivalent 2-position-CHs, and equivalent -CHs in the 3-position). The aromatic region also displays the typical *ortho*-disubstituted phenyl fingerprint associated with the

boryl group ( $\delta_B$  34) with a chemical shift coincidental with the structurally characterised 1b, and the related bifunctional species 2a. The mass spectrometry data are in accordance with the spectral inferences implied by NMR; the calculated and measured masses (including accurate mass experiments) are virtually identical. The spectroscopic data combined with the results of the X-ray diffraction data confirm the structure of 2b, represented pictorially in Figure 3.8. Relevant bond lengths and angles are noted in Table 3.5.



Figure 3.8 Molecular structure of  $(\eta^5-C_5H_5)Fe[\eta^5-C_5H_4BO_2C_6H_4]$  (2b). ORTEP ellipsoids set at the 30% probability level; hydrogen atoms omitted for clarity.

Fe(1)-C(1)	2.053(3)	C(11)-C(16)	1.377(3)
Fe(1)-C(6)	2.033(3)	C(1)-C(2)	1.422(4)
O(1)-B(1)	1.398(4)	C(6)-C(7)	1.441(4)
O(2)-B(1)	1.398(4)	O(2)-C(16)	1.389(3)
B(1)-C(6)	1.519(4)	O(1)-C(11)	1.383(3)
		· · · · · · · · · · · · · · · · · · ·	
B(1)-O(1)-C(11)	105.0(2)	O(1)-C(11)-C(16)	109.7(2)
B(1)-O(1)-C(11) B(1)-O(2)-C(16)	105.0(2) 104.9(2)	O(1)-C(11)-C(16) O(2)-C(16)-C(11)	109.7(2) 109.4(2)
B(1)-O(1)-C(11) B(1)-O(2)-C(16) O(1)-B(1)-O(2)	105.0(2) 104.9(2) 111.0(2)	O(1)-C(11)-C(16) O(2)-C(16)-C(11) C(7)-C(6)-B(1)	109.7(2) 109.4(2) 126.7(3)
B(1)-O(1)-C(11) B(1)-O(2)-C(16) O(1)-B(1)-O(2) O(1)-B(1)-C(6)	105.0(2) 104.9(2) 111.0(2) 124.2(3)	O(1)-C(11)-C(16) O(2)-C(16)-C(11) C(7)-C(6)-B(1) C(10)-C(6)-B(1)	109.7(2) 109.4(2) 126.7(3) 125.4(3)
B(1)-O(1)-C(11) B(1)-O(2)-C(16) O(1)-B(1)-O(2) O(1)-B(1)-C(6) O(2)-B(1)-C(6)	105.0(2) 104.9(2) 111.0(2) 124.2(3) 124.8(3)	O(1)-C(11)-C(16) O(2)-C(16)-C(11) C(7)-C(6)-B(1) C(10)-C(6)-B(1) C(8)-C(9)-C(10)	109.7(2) 109.4(2) 126.7(3) 125.4(3) 107.8(2)

Table 3.5 Bond distances (Å) and angles (°) for 2b.

The crystal structure of 2b is such that many of the salient parameters listed in Table 3.5 are comparable to those of 1b. Fe-C(Cp) bond lengths are similar to those found for 1b and the 1,3-propane-diol based cyclic boronate  $FcB[O_2(CH_2)_3]$ .<sup>20</sup> Boron-oxygen bond distances are also comparable with these systems, and the O-B-O angle in 2b [111.0(2)°] is comparable to that of compound 1b [113.1(4)°]. The orientation of the boryl function in 2b displays a rather interesting feature that is not observed in the structures of other oxygen-substituted borylferrocenes. In this case, it is clear that the trigonal planar boryl moiety is tilted out of the plane of the cyclopentadienyl ligand by an angle of 13.3°. This bending of the boryl group towards the iron centre has also been witnessed in the crystal structures of 1,1'-fc(BBr<sub>2</sub>)<sub>2</sub> and FcBBr<sub>2</sub> in which corresponding angles are 10.2° and 17.7°.<sup>24,25</sup> This phenomenon has been attributed to a weak donor/acceptor interaction between filled

molecular orbitals on the iron centre and the vacant  $p_z$  orbital at boron. Given the expected Lewis acidities of the two compounds [FcBBr<sub>2</sub> > FcBO<sub>2</sub>C<sub>6</sub>H<sub>4</sub>], and therefore the relative demand for electron density by the boron atoms in these systems, it is not surprising that the out of Cp-plane bending of the boryl moiety in **2b** is significantly smaller than that seen in the solid state structure of FcBBr<sub>2</sub>. Further comparison of this out of Cp-plane bending displayed by **2b** can be made with the structurally characterised systems **1b** (1.7°) and ferroceneboronic acid (4.3°).<sup>26</sup> In doing so, it is observed that the magnitude of bending occurs such that: FcBBr<sub>2</sub> > FcBO<sub>2</sub>C<sub>6</sub>H<sub>4</sub> (**2b**) > FcB(OH)<sub>2</sub>  $\approx$  Fc[B(OCHPh)<sub>2</sub>] (**1b**), thus reflecting the extent of the electron donor/acceptor interaction between iron and boron in these systems. The greater bending angle observed in **2b** compared with **1b** signifies a boron centre of greater Lewis acidity (for **2b**), presumably as a result of conjugation of the lone electron pairs of the oxygen atoms into the aromatic system of the catechol ring.

## 3.3.4 Electrochemistry of mono-borylferrocenes

Electrochemical studies were also performed on the mono-boryl species 1b and 2b to determine how the oxidation potential varies with the number of boryl moieties linked to ferrocene. These measurements allow a direct comparison with the respective bis-boryl systems (1a and 2a) to be made. CV measurements were performed in either dichloromethane or acetonitrile solution with ferrocene as the reference. The electrochemical sweeps for compounds 1b and 2b are shown in Figures 3.9 and 3.10 respectively, with a summary of relevant parameters collected in Table 3.6.



Figure 3.10 Cyclic Voltammogram of 2b in MeCN with  $[^{n}Bu_{4}N]PF_{6}(0.1 \text{ M})$  as supporting electrolyte. Scan rate = 100 mV/s.



Compound	Solvent	Peak-Peak separation (Ep <sup>ox</sup> -Ep <sup>red</sup> ) (mV)	E <sub>1/2</sub> Relative to FcH (E <sub>1/2</sub> Ref.) (mV) <sup>a</sup>
1b	DCM	91	+131
1b	MeCN	81	+116
2b	MeCN	161	+86

Table 3.6 Electrochemical data of mono-borylferrocenes 1b and 2b with $["Bu_4N]PF_6 (0.1 M)$  as supporting electrolyte .

<sup>a</sup> FcH vs S.C.E:  $E_{1/2} = 0.46$  V (DCM), 0.40 V(MeCN)

In the cases of both mono-substituted ferrocenes, the respective electrochemical scans exhibit reversible oxidation processes. Of particular interest is the value of the oxidation potential with respect to ferrocene. As one might expect, the inherent Lewis acidity of the boryl groups serves to withdraw electron density from both the neighbouring oxygen substituents and the cyclopentadienyl ligand, rendering the iron centre less electron rich. The resultant effect is that oxidation occurs at a more positive potential (+116 mV for 1b, +86 mV for 2b in MeCN) relative to ferrocene.

Furthermore, the electron withdrawing effect in systems featuring just one boryl group is expected to be less than those featuring two such functions. This is manifested in the position of the observed oxidation potentials of bidentate bisboronic ester compounds [1a (+222 mV) and 2a (+92 mV) with respect to FcH/[FcH]<sup>+</sup>], compared with the mono-borylferrocene analogues [1b (+131 mV) and 2b (+86 mV) with respect to FcH/[FcH]<sup>+</sup>].

A final observation was made in the cyclic voltammetry scans of the monoand bis- catecholato-borylferrocenes. When the scan width was extended to higher positive potentials, non-reversible electrochemical behaviour was observed at ca. 1 V for 2a and 800 mV for 2b. These oxidation processes appear characteristic of catechol-based electrochemistry, in which oxidation to the corresponding quinone takes place.

## 3.3.5 Mono-boryl Lewis acids based on cymantrene

Similar synthetic routes have been utilised in the formation of cymantrene  $[CpMn(CO)_3]$  based boronic esters, thereby giving access to the Lewis acids 7 and 8 (Scheme 3.8). Borylation of  $CpMn(CO)_3$  with boron tribromide is readily accomplished according to the route of Siebert *et. al.*<sup>10</sup> Subsequent reaction of the -BBr<sub>2</sub> derivative with the respective dilithiated-diol generates the cymantrene-functionalized cyclic boronates 7 and 8 in 53 % and 18 % (unoptimised) yields respectively. Both are moderately air-sensitive compounds and are best-stored under inert atmosphere in which case they are stable indefinitely.



Scheme 3.8 Synthetic routes to cymantrene-based Lewis acids.

 $[\eta^5-C_5H_4B(OCHPh)_2]Mn(CO)_3$  (7) is a pale yellow crystalline solid, unstable under aerobic conditions. Spectroscopic characterisation including <sup>1</sup>H and <sup>13</sup>C NMR are in accordance with the presence of a chiral pendant boryl group, displaying the expected four distinct cyclopentadienyl -CH resonances. The <sup>11</sup>B NMR spectrum displays a broad singlet at  $\delta_{\rm B}$  31.0, comparable with the boryl systems based on ferrocene, and indicative of a Cp pendant trigonal boron with two oxygen substituents. Mass spectrometry data provide further evidence for the nature of 7, in that the molecular ion peak, and appropriate isotopic pattern are closely matched with theoretical calculations. Of particular interest is the infrared spectrum, and the positions of the CO stretching frequencies. The proposed structure and symmetry (Scheme 3.7) implies three such stretching modes, which are apparent in the spectrum as the v(CO symmetric) peak at 2028 cm<sup>-1</sup>, and a broadened peak at 1949 cm<sup>-1</sup> [overlap of both v(CO asymmetric)]. Relative to cymantrene itself [ $v_{co}$ =2023, 1939 cm<sup>-1</sup> (KBr)],<sup>27</sup> these frequencies are at higher wavenumber, which can be attributed to the electron withdrawing effect of the boryl group rendering the manganese centre less electron rich, so that  $\pi$ -backbonding to the carbonyl ligands is reduced.

Compound 8 [ $\eta^5$ -C<sub>5</sub>H<sub>4</sub>BO<sub>2</sub>C<sub>6</sub>H<sub>4</sub>]Mn(CO)<sub>3</sub> is also a pale yellow crystalline solid, unstable in air, although stable under inert atmosphere over prolonged periods. <sup>1</sup>H and <sup>13</sup>C NMR spectra are in agreement with the proposed formulation, with the expected signature for the boryl-substituted Cp and *ortho*-disubstituted phenyl substituents being observed. The <sup>11</sup>B NMR spectrum displays a single broad resonance with a chemical shift ( $\delta_B$  30.8) which correlated with structurally characterised mono- and bis-borylferrocene species as well as with complex 7. The mass spectrometry data (including accurate mass determination) support the inferences from the NMR spectra, with the calculated and measured masses in close
#### Chapter Three The Synthesis and Characterisation of Monoand Bifunctional Boron-Containing Lewis Acids

agreement. As in the case of related cymantrene derivative 7, the symmetric and asymmetric CO stretching frequencies are again at slightly higher wavenumbers relative to  $CpMn(CO)_3$ , (2025 cm<sup>-1</sup> and 1955 cm<sup>-1</sup>).

## 3.4 Conclusions and suggestions for further research

The synthesis of the bidentate bis-boronic ester derivatives (1a-5a) can be accomplished in reasonable yield and with high purity to generate a series of derivatives in which the electronic and structural properties of the boryl substituents can be varied. Comparison of the structure of the bis-borylferrocene 1a with other structurally characterised cyclic boronates fc[B(OCH<sub>2</sub>)<sub>2</sub>]<sub>2</sub> and {fc[Bpinanediolate]<sub>2</sub>}<sup>20</sup> reveal that the B-centroid-centroid'-B' torsion angle, and hence the B...B distance in these cases is likely to be largely dependent on the packing efficiency of the molecules in the solid state.

The successful synthesis of the corresponding mono-boronic ester derivatives has allowed a comparison of structural parameters with bidentate analogues, and also enabled a detailed analysis of electronic effects associated with the respective boryl substituents. The use of cyclic voltammetry for ferrocene-based systems has proved invaluable in assessing the electron withdrawing effect of the various electron deficient boronic esters. The electrochemical results demonstrate that the nature of the diolate used has a profound effect on the redox chemistry of the ferrocene moiety, as does the number of such pendant groups. A large anodic shift in the oxidation potential is observed on adding each successive boryl substituent.

In the case of the boryl-cymantrenes 7 and 8, synthesis *via* direct borylation and subsequent substitution at boron generates these species in reasonable yields. The presence of the carbonyl groups enables the electronic effect of Lewis acidic boron to

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be analysed by the alternative technique of infrared spectroscopy, and a comparison with the parent  $CpMn(CO)_3$  to be carried out. Once again, the infrared spectrum demonstrates clearly the electron withdrawing properties of the boryl function as manifested by a shift in the position of the symmetric and asymmetric CO stretching frequencies to higher wavenumber.

Mindful of these initial results and the successful preparation of mono- and bidentate-boryl species, it may prove interesting to synthesise the corresponding trisand tetrakis-boryl ferrocene systems, since the tri- and tetra-borylation of ferrocenes with boron halides has been previously reported.<sup>14,28</sup> Thus, reaction of the tris- and tetrakis-dihaloboryl species with three or four equivalents respectively of a lithiated diol may allow access to multi-boronic ester derivatives.

As a route to improving the yields of the various syntheses, it may prove useful to utilise the alternative reaction pathways that have been alluded to as the second method of preparation of compound 5a, and the synthesis of the bridged species 6 via a trimethylsilyl precursor. In the case of the condensation reaction between the napthalene-based diol with 1,1'-ferrocene-diboronic acid, the successful synthesis of 5a was evident from spectroscopic analyses. However, the problem of obtaining relatively pure samples of fc[B(OH)<sub>2</sub>]<sub>2</sub> limited the yield in this case.

Alternatively, the use of trimethylsilyl-substituted precursors of the various diol-starting materials (as applied to the preparation of 6) might prove advantageous in increasing yields, and eliminating potential hydrolysis by removing traces of moisture present in the diol starting material. Reaction of the TMS-diol species with the mono- or bis-(dibromoboryl)metallocene, should yield the desired product and TMS-bromide, which can be subsequently removed *in vacuo*. More recently, the use of triethylamine in place of *n*-butyllithium as base has been well demonstrated by

#### Chapter Three The Synthesis and Characterisation of Monoand Bifunctional Boron-Containing Lewis Acids

Aldridge, Fallis and Coombs; in synthesising ferrocenyl mono- and bis- boronic esters of ethane-1,2-diol, propane-1,3-diol and the chiral pinanediol.<sup>20</sup> Bearing in mind the scope of the various syntheses described in this chapter, it may transpire that certain pathways are more effective in the synthesis of particular cyclic boronic esters based on ferrocene than others, since the most convenient route is often the best route.

#### 3.5 References for Chapter Three

- 1. S. Aldridge, C. Bresner, Coord. Chem. Rev., 2003, 244, 71-92.
- H. Yamamoto, A. Ori, K. Ueda, C. Dusemond, S. Shinkai, *Chem. Commun.*, 1996, 407.
- 3. M. Bochmann, S. J. Lancaster, O. B. Robinson, Chem. Commun., 1995, 2081.
- 4. K. A. Rufanov, V. V. Kotov, N. B. Kazennova, D. A. Lemenovskii, E. V. Avtomonov, J. Lorberth, J. Organomet. Chem., 1996, **525**, 287.
- D. S. Stelck, P. J. Shapiro, N. Basickes, A. L. Rheingold, Organometallics, 1997, 16, 4546.
- S. A. Larkin, J. T. Golden, P. J. Shapiro, G. P. A. Yap, D. M. J. Foo, A. L. Rheingold, Organometallics, 1996, 15, 2393.
- 7. G. E. Herberich, A. Fischer, D. Wiebelhaus, Organometallics, 1996, 15, 3106.
- G. E. Herberich, U. Englert, A. Fischer, D. Wiebelhaus, Organometallics, 1998, 17, 4769.
- 9. H. Braunschweig, T. Wagner, Chem. Ber., 1994, 127, 1613.
- 10. T. Renk, W. Ruf, W. Siebert, J. Organomet. Chem., 1976, 120, 1-25.
- 11. W. Ruf, T. Renk, W. Siebert, Z. Naturforsch. Teil B, 1976, 31, 1028.
- H. Braunschweig, R. Dirk, M. Müller, P. Nguyen, R. Resendes, D. P. Gates, I. Manners, Angew. Chem. Int. Ed. Engl., 1997, 36, 2338.
- 13. F. Jäkle, A. Berenbaum, A. J. Lough, I. Manners, Chem. Eur. J., 2000, 6, 2762.
- 14. A. Appel, H. Nöth, M. Schmidt, Chem. Ber., 1995, 128, 621.
- 15. M. Herberhold, U. Dörfler, W. Milius, B. Wrackmeyer, J. Organomet. Chem., 1995 492, 59.
- 16. S. Guo, J. W. Bats, M. Bolte, M. Wagner, J. Chem. Soc., Dalton Trans., 2001, 3572.

- 17. A. N. Nesmeyanov, V. A. Sazonowa, V. N. Drozd, *Dokl. Akad. Nauk SSSR*, 1959, **126**, 1004.
- 18. S. Aldridge, C. Bresner, I. A. Fallis, S. J. Coles, M. B. Hursthouse, Chem. Commun., 2002, 740.
- 19. R Knapp, M. Rehahn, J. Organomet. Chem., 1993, 452, 235.
- 20. S. Aldridge, I. A. Fallis, N. D. Coombs, unpublished results.
- K. Akiba, M. Yamshita, Y. Yamamoto, S. Nagase, J. Am. Chem. Soc., 1999, 121, 10644.
- 22. K. B. Sharpless, Chem. Rev., 1994, 94, 2483.
- B. E. Carpenter, W. E. Piers, R. McDonald, Can. J. Chem., 2001, 79, 291; B. E. Carpenter, W. E. Piers, M. Parvez, G. P. A. Yap, S. J. Rettig, Can. J. Chem., 2001, 79, 857.
- 24. B. Wrackmeyer, U. Dörfler, W. Milius, M. Herberhold, Polyhedron, 14, 1995, 1425.
- A. Appel, F. Jäkle, T. Priermeier, R. Schmid, M. Wagner, Organometallics, 1996, 15, 1188.
- 26. C. Bresner, S. Aldridge, I. A. Fallis, L. Ooi, Acta Cryst., 2004, E60, 1.
- 27. D.M. Adams, A. Squire, J. Organomet. Chem., 1973, 63, 381.
- 28. B. Wrackmeyer, U. Dörfler, M. Herberhold, Z. Naturforsch., Teil B, 1993, 48, 121.

## **Chapter Four**

# Fluoride Binding by Mono- and Bifunctional Boron-Containing

**Lewis Acids** 

# 4.1 Introduction

The selective binding or recognition of anions continues to be a challenging area in the field of supramolecular chemistry, in part due to the relatively high solvation energies associated with such species. In comparison to the coordination chemistry involved in cation complexation with Lewis bases,<sup>1</sup> analogous studies of anion complexation have received less attention. However, in recent years the literature has witnessed a growing interest in this field and several recent reviews have concentrated on this area.<sup>2</sup> Reasons for this surge of interest include potential applications in anion separation technologies and in sensors, as well as the significant roles that anions play in biological and environmental processes. Fluoride ion recognition in particular has experienced a great deal of attention from various research groups, due to its relevance to health and environmental issues. Furthermore, the specific affinity that fluoride demonstrates for boron based receptors,<sup>3-10</sup> and the relatively strong bonds that can be formed with hydrogen bond donors,<sup>11-16</sup> both encourage such interest.

Within the scope of this project, the coordination of anionic species to Lewis acidic boron-based receptors appears attractive. One of the earlier examples of an interaction of this type was reported by Katz;<sup>5</sup> fluoride complexation was observed by a mixed boron/silicon bidentate system based on a 1,8 disubstituted napthalene backbone (I, Scheme 4.1). It was found that treatment of I with a source of fluoride resulted in the formation of a boron-fluorine bond and a significant degree of

interaction between the bound fluoride and the neighbouring silicon moiety, both in the solid state and in solution.



Scheme 4.1 A fluoride host-guest complex II, reported by Katz in 1986.

An alternative investigation by Solé and Gabbaï has demonstrated colorimetric fluoride ion sensing using Lewis acid boryl groups also linked via a napthalene unit (Scheme 4.2, III).<sup>6</sup> In this case, fluoride coordination has been shown by X-ray diffraction to occur in bidentate fashion (IV), bridging between the two boron centres. In the absence of fluoride the receptor appears bright yellow in chloroform solution, undergoing a change to colourless selectively in the presence of fluoride.



Scheme 4.2 Selective colorimetric recognition of fluoride via anion chelation.

Recently, Yamaguchi and co-workers have developed boron-containing  $\pi$ electron systems capable of sensing fluoride *via* a colorimetric response.<sup>7</sup> The compounds under investigation included trianthrylborane (V, orange), and dimesitylboryl-substituted trianthrylborane (VI, red) (Figure 4.1). These were found to coordinate one and three equivalents of fluoride respectively with colour changes to colourless and orange in solution.



Figure 4.1 Trianthrylborane (V) and dimesitylboryl-substituted trianthrylboranes (VI) as colorimetric fluoride ion sensors.

More recent studies by the same group have concentrated on fluoride binding by alternative  $\pi$ -electron systems, based around dibenzoborole frameworks (Scheme 4.3, VII).<sup>8</sup> In this case, the fluorescence properties (wavelength and intensity) were found to be highly dependent on the solvent system, such that donor solvents (DMF, THF) cause significant changes in their fluorescence spectra due to coordination to boron. Addition of fluoride as the tetra-*n*-butylammonium salt in THF solution revealed further changes in the fluorescence properties attributable to fluoride complexation to form the adduct VIII.



Scheme 4.3 Dibenzoborole systems as fluorescent fluoride sensors by Yamaguchi *et. al.* 

The group of Davidson has also developed a selective bidentate, fluorescent fluoride sensor (IX, Figure 4.2).<sup>9</sup> In this case, the sensor possesses two boryl moieties attached to a robust calixarene framework, such that the boron centres are an appropriate distance apart to bind fluoride in a bidentate fashion. The boron-bound phenyl groups of the bis(bora)calixarene provided sufficient fluorescence intensity such that the process of fluoride binding could be monitored *via* fluorescence spectroscopy. Treatment with fluoride resulted in quenching of the fluorescence, and titration techniques concluded that a 1:1 bidentate complex with fluoride is thus formed. Furthermore, the selectivity of the system was demonstrated by treatment with the alternative halides, which caused no significant changes in the fluorescence spectrum.





The use of fluorescence spectroscopy in the detection of anionic species (by fluorescence quenching) has also been independently studied by the group of James. The specific affinity of the boronic acid group towards fluoride was exploited in the investigation of fluoride binding to the boronic acids illustrated in Figure 4.3,<sup>10</sup> which include phenylboronic acid X, and 2-napthylboronic acid XI.



Figure 4.3 Boronic acids for fluoride detection by fluorescence spectroscopy, James et. al., 1998.

Fluorescence titration experiments for X and XI with fluoride (as KF) allowed the determination of stability constants for formation of the corresponding trifluoro tetrahedral boronates *i.e.* ArBF<sub>3</sub><sup>-</sup> (1.04 x  $10^4$  and 1.08 x  $10^4$  dm<sup>9</sup> mol<sup>-3</sup> respectively). In addition, the boronic acid XII was thought to promote a stronger binding of one fluoride ion through participation of hydrogen bonding when the amine is protonated, at pHs < 5.5 (*i.e.* the  $pK_a$  of the amine). The result was a binding constant of 101 dm<sup>3</sup> mol<sup>-1</sup>, which assumed formation of a mono-fluoride adduct at pH 5.5. <sup>11</sup>B and <sup>19</sup>F NMR spectroscopy confirmed the results observed from the fluorescence measurements, indicating formation of mono-fluoride adducts (on addition of one equivalent of KF), and trifluorinated-boronate species when the respective compounds were treated with five equivalents of KF.

Perhaps the most relevant investigation with respect to the work presented in this thesis was carried out by the group of Shinkai *et. al.*<sup>4</sup> Commercially available ferroceneboronic acid (XIII, Figure 4.4) was shown to electrochemically detect fluoride in water even when the other halides were present in high concentration. Boronic acids are known to possess a particular affinity for fluoride, and by coupling this together with a redox active centre (ferrocene), it was possible to monitor the anion complexation process by cyclic voltammetry measurements. In this case  $F^-$  coordination was characterised by a shift of *ca.*-100 mV in the redox potential in aqueous media.

Figure 4.4 Redox active ferroceneboronic acid displays particular affinity for fluoride.



XIII

## 4.1.1 Aims of the present research

In view of recent advances in the recognition of specific anionic species and the significance of the challenge to the modern day chemist, it was decided to examine the possibility for Lewis base/anion binding using the ferrocene-based boryl compounds synthesised in Chapter Three (see Figure 4.5). The fact that Cp-pendant boronic acids and esters have significant affinity for fluoride, coupled with the electrochemical and spectroscopic properties of the ferrocene moiety, should mean that complexation and monitoring processes are both feasible. The decision to probe fluoride binding by bifunctional boryl systems as well as by monofunctional receptors reflects the desire to achieve stronger binding by anion chelation (*i.e.* a coordination "umpolung" of the chelate effect). Furthermore, ready modification of the substituents about boron may result in variations in anion recognition behaviour, and allow alternative spectroscopic monitoring of the anion binding process, for example, by fluorescence.



Figure 4.5 Mono- and bis-boronic esters of ferrocene, and mono-boronic esters of cymantrene synthesised in Chapter Three.

#### 4.2 Experimental

# NMR analysis of fluoride binding to bifunctional Lewis acids 1a, 2a, 3a, 4a, 5a

A sample of the respective Lewis acid (typically 20 mg, 0.035 mmol for 5a) was weighed into a Young's NMR tube under anaerobic conditions, dissolved in dry, degassed CDCl<sub>3</sub>, and the compound checked by <sup>11</sup>B and <sup>1</sup>H NMR prior to fluoride addition. Tetra-*n*-butylammonium fluoride hydrate (1 equivalent, 9 mg, 0.035 mmol for 5a) was added to the Young's NMR tube whilst under argon, mixed for 15 min, and the <sup>11</sup>B and <sup>1</sup>H NMR spectra measured again. At this stage, <sup>11</sup>B NMR of the yellow/orange mixture indicated the presence of both three coordinate ( $\delta_B$  31 for 5a) and fluoride-bound boron centres ( $\delta_B$  7.6 for 5a). Another equivalent of [<sup>*n*</sup>Bu<sub>4</sub>N]F (9 mg, 0.035 mmol for 5a) was added quickly as a solid to the NMR tube under argon atmosphere and mixed for 15 min, followed by spectral acquisition. The <sup>11</sup>B NMR spectrum now revealed a single broad resonance ( $\delta_B$  7.9 for 5a) for the fluoride adduct, with no trace of starting material present. Resonances in the <sup>1</sup>H NMR spectrum.

In the case of compound 1a, treatment of the Lewis acid with an alternative fluoride source of potassium fluoride with 18-crown-6, yielded identical spectroscopic results to those observed with ["Bu<sub>4</sub>N]F, the fluoride adduct appearing as a single broad resonance at  $\delta_{\rm B} = 10.8$ .

# Spectroscopic data for 1a + 2 equivalents of $["Bu_4N]F$

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta$  0.91 [br m, 12H, CH<sub>3</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.32 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.42 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 3.07 [br m, 8H, NCH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 4.20 [br m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.42 [br m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.54 [br m, 2H,

CH of C<sub>5</sub>H<sub>4</sub>], 4.65 [br m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.89 [br s, 2H, CH of chelate], 7.15-7.36 [br m, 10H, C<sub>6</sub>H<sub>5</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  9.4; <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  –133.7.

# Spectroscopic data for 1a +2 equivalents of KF/18-crown-6

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta$  3.48 [br s, 18-crown-6], 4.24 [br m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.48 [br m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.61 [br m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.73 [br m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 5.04 [br s, 2H, CH of chelate], 7.28-7.41 [br m, 10H, C<sub>6</sub>H<sub>5</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  9.3; <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  –130.8.

# Spectroscopic data for 2a + 2 equivalents of $[^{n}Bu_{4}N]F$

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta$  0.94 [m, 12H, CH<sub>3</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.31 [m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.35 [m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 2.88 [br m, 8H, NCH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 4.09 [m, 4H, CH of C<sub>5</sub>H<sub>4</sub>], 4.28 [m, 4H, CH of C<sub>5</sub>H<sub>4</sub>], 6.59-6.67 [m, 4H, C<sub>6</sub>H<sub>4</sub>], 6.75-6.87 [m, 4H, C<sub>6</sub>H<sub>4</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  10.2 (br); <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  –127.9.

# Spectroscopic data for 3a + 2 equivalents of $[{}^{n}Bu_{4}N]F$

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta$  0.84 [m, 12H, CH<sub>3</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.11 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.26 [m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.35 [br s, 18H, 'Bu], 1.48 [br s, 18H, 'Bu], 2.56 [br m, 8H, NCH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 4.05 [br m, 4H, CH of C<sub>5</sub>H<sub>4</sub>], 4.12 [br m, 4H, CH of C<sub>5</sub>H<sub>4</sub>], 6.47 [m, 2H, C<sub>6</sub>H<sub>2</sub>], 6.58 [m, 2H, C<sub>6</sub>H<sub>2</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  10.2 (br); <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  –129.0.

# Spectroscopic data for 4a + 2 equivalents of $[^{n}Bu_{4}N]F$

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta$  0.88 [m, 12H, CH<sub>3</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.19 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.32 [m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 2.72 [br m, 8H, NCH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 3.59 [s, 3H, OCH<sub>3</sub>], 4.13 [br m, 4H, CH of C<sub>5</sub>H<sub>4</sub>], 4.22 [br m, 4H, CH of C<sub>5</sub>H<sub>4</sub>], 6.24 [br m, 2H, C<sub>6</sub>H<sub>3</sub>], 6.39 [br m, 2H, C<sub>6</sub>H<sub>3</sub>], 6.58 [br m, 2H, C<sub>6</sub>H<sub>3</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  10.5 (br); <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  –128.7.

# Spectroscopic data for 5a + 2 equivalents of $["Bu_4N]F$

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta 0.88$  [m, 12H, CH<sub>3</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.26 [m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.31 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 2.92 [br m, 8H, NCH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 4.04 [br m, 2H, CH<sub>2</sub> of chelate], 4.12 [br m, 4H, CH of C<sub>5</sub>H<sub>4</sub>], 4.29 [m, 4H, CH of C<sub>5</sub>H<sub>4</sub>], 4.40 [br m, 2H, CH<sub>2</sub> of chelate], 4.97 [br m, 1H, CH of chelate], 7.38-7.42 [m, 6H, C<sub>10</sub>H<sub>7</sub>], 7.74-7.78 [m, 8H, C<sub>10</sub>H<sub>7</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  8.0 (br); <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  –134.3.

# NMR analysis of fluoride binding to monofunctional Lewis acids 1b, 2b, 7, 8

An analogous method was used for the binding of fluoride by mono-boryl systems 1b, 2b, 7 and 8. In these cases, the Lewis acid (typically 20 mg, 0.066 mmol for 2b) was dissolved in dry CDCl<sub>3</sub> under anaerobic conditions, and the <sup>11</sup>B and <sup>1</sup>H NMR spectra measured (to confirm the purity of the starting material). [<sup>*n*</sup>Bu<sub>4</sub>N]F (0.5 equivalents, 8.6 mg, 0.033 mmol for 2b) was then quickly added to the solution of the Lewis acid as a solid, and the <sup>11</sup>B and <sup>1</sup>H NMR spectra measured again (this time indicating a mixture of starting material and product). A further addition of [<sup>*n*</sup>Bu<sub>4</sub>N]F (0.5

equivalents) aided complete conversion to the fluoride adduct, evident in the <sup>11</sup>B NMR spectrum as an upfield shift of ca. 25 ppm relative to the free Lewis acid.

# Spectroscopic data for 1b + l equivalent of $["Bu_4N]F$

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta$  0.86 [m, 12H, CH<sub>3</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.24 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.28 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 2.91 [br m, 8H, NCH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 4.09 [m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.19 [s, 5H, CH of C<sub>5</sub>H<sub>5</sub>], 4.30 [m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.71 [br s, 2H, CH of chelate], 7.18-7.33 [br m, 10H, C<sub>6</sub>H<sub>5</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  9.1 (br); <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  -136.1.

# Spectroscopic data for **2b** +1 equivalent of ["Bu<sub>4</sub>N]F

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta$  0.94 [m, 12H, CH<sub>3</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.32 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.41 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 2.94 [br m, 8H, NCH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 3.99 [m, 2H, CH of C<sub>3</sub>H<sub>4</sub>], 4.10 [s, 5H, CH of C<sub>3</sub>H<sub>5</sub>], 4.14 [m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 6.48 [m, 2H, C<sub>6</sub>H<sub>4</sub>], 6.56 [m, 2H, C<sub>6</sub>H<sub>4</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  10.0; <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  –128.5.

# Spectroscopic data for 7 + 1 equivalent of $[^{n}Bu_{4}N]F$

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta$  0.90 [m, 12H, CH<sub>3</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.31 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.44 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 3.05 [br m, 8H, NCH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 4.61 [br m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.63 [br m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.91 [m, 2H, CH of chelate], 7.20-7.32 [br m, 10H, C<sub>6</sub>H<sub>5</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  6.41 (br); <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  –135.6.

# Spectroscopic data for 8 + 1 equivalent of $[^nBu_4N]F$

<sup>1</sup>H NMR ([D]chloroform, 300 MHz, 20°C),  $\delta$  0.96 [m, 12H, CH<sub>3</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.36 [m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 1.52 [br m, 8H, CH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 3.10 [br m, 8H, NCH<sub>2</sub> of "Bu<sub>4</sub>N<sup>+</sup>], 4.61 [m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 4.77 [m, 2H, CH of C<sub>5</sub>H<sub>4</sub>], 6.51 [m, 2H, C<sub>6</sub>H<sub>4</sub>], 6.57 [m, 2H, C<sub>6</sub>H<sub>4</sub>]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  8.2 (br); <sup>19</sup>F NMR ([D]chloroform, 283 MHz, 20°C),  $\delta$  –130.2.

# <sup>1</sup>H NMR titrations of fluoride binding to compounds 1a and 1b</sup>

Anaerobic <sup>1</sup>H NMR titrations were carried out for compounds **1a** and **1b** by monitoring the chemical shift of the methine protons of the cyclic boronate backbone. On treatment of the respective Lewis acid with fluoride, the methine singlet is found to shift to lower  $\delta$  on the addition of successive aliquots of fluoride as solid ["Bu<sub>4</sub>N]F. The Lewis acid **1a** (120 mg, 0.19 mmol) was weighed into a Young's NMR tube, dried *in vacuo* and dissolved in dry, degassed CDCl<sub>3</sub>. The <sup>11</sup>B and <sup>1</sup>H NMR were initially recorded in absence of fluoride, then <sup>1</sup>H NMR were recorded after the successive addition of 0.1, 0.2, 0.3, and 0.4 equivalents of ["Bu<sub>4</sub>N]F, under anaerobic conditions with mixing between fluoride additions and spectral acquisition. Further <sup>1</sup>H NMR were measured after the addition of 0.6, 0.8, 1.0,...3.0 equivalents of ["Bu<sub>4</sub>N]F (0.2 equivalent intervals), with adequate mixing prior to recording the <sup>1</sup>H NMR spectra. The same procedure was performed for the <sup>1</sup>H NMR titration of **1b** with fluoride addition. However, in this case, ["Bu<sub>4</sub>N]F was added as 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, ...2.0 equivalents to a solution of the Lewis acid **1b** (100 mg, 0.25 mmol) in CDCl<sub>3</sub>, under an argon atmosphere. Data were fitted using WIN EQNMR.<sup>17</sup>

#### Electrochemical analysis of fluoride binding to 1a, 1b, 2a, 2b, 3a, 4a, 5a

Electrochemical analysis was carried out using the following conditions: electrolyte, 0.1 M [ $^{n}Bu_{4}N$ ][PF<sub>6</sub>] in dichloromethane or acetonitrile; reference electrode standard, 0.1 M [ $^{n}Bu_{4}N$ ][PF<sub>6</sub>], 0.01 M silver nitrate in acetonitrile. Following degassing of the electrolyte solution with argon, background cyclic voltammetry (CV) scans were measured and a small sample (*ca.* 2-5 mg) of the Lewis acid was added to the solution. Further degassing served to purge the solution of any additional dissolved oxygen and agitate the solid Lewis acid to dissolve the compound, prior to spectral acquisition. Further CV scans were measured on the addition of aliquots of solid [ $^{n}Bu_{4}N$ ]F, and on addition of ferrocene as a reference.

# UV/Vis analysis of fluoride binding

A sample of the Lewis acid was dissolved in degassed chloroform under anaerobic conditions to give a solution of *ca*. 5 mM concentration. This was then transferred to the UV cell under argon and the spectrum measured. An excess of  $[^{n}Bu_{4}N]F$  was then added to the solution which was stirred for 20 min. under aerobic conditions and the UV spectrum measured again.

**1a**:  $\lambda = 341, 449 \text{ nm}, \mathbf{1a} + [^{n}\text{Bu}_{4}\text{N}]\text{F}: \lambda = 428, 629 \text{ nm}.$ 

- **2a**:  $\lambda = 337$ , 441 nm, **2a**+[<sup>*n*</sup>Bu<sub>4</sub>N]F:  $\lambda = 425$ , 610 nm.
- **3a**:  $\lambda = 339$ , 444 nm, **3a**+[<sup>*n*</sup>Bu<sub>4</sub>N]F:  $\lambda = 382$ , 620 nm.
- **4a**:  $\lambda = 342, 451$  nm, **4a**+[<sup>*n*</sup>Bu<sub>4</sub>N]F:  $\lambda = 442$  nm.
- **5a**:  $\lambda = 335$ , 447 nm, **5a**+[<sup>*n*</sup>Bu<sub>4</sub>N]F:  $\lambda = 425$ , 625 nm.
- **1b**:  $\lambda = 450$  nm, **1b**+["Bu<sub>4</sub>N]F:  $\lambda = 431$  nm.
- **2b**:  $\lambda = 448$  nm, **2b**+["Bu<sub>4</sub>N]F:  $\lambda = 433$  nm.

## Monitoring of fluoride binding to 5a by fluorescence spectroscopy

Following acquisition of a background emission spectrum of acetonitrile in a 0.5 cm<sup>3</sup> fluorescence cell, a solution of the parent diol, namely 1-(2-napthyl)-1,2-ethanediol (10 mg, 0.053 mmol) in acetonitrile (100 cm<sup>3</sup>, 5.3 x 10<sup>-4</sup> M) was prepared, and the emission spectrum measured ( $\lambda_{ex} = 210$  nm,  $\lambda_{em} = 330$  nm). A 0.02 M solution of compound **5a** (6 mg, 0.01 mmol) in acetonitrile (0.5 cm<sup>3</sup>), was then transferred to the empty fluorescence cell, and the averaged emission spectrum of 10 scans recorded ( $\lambda_{ex} = 210$  nm,  $\lambda_{em} = 370$  nm). An excess of solid ["Bu<sub>4</sub>N]F (>2 equivalents) was then added to the solution, and the emission spectrum recorded at 15 minute intervals over a three hour period ( $\lambda_{ex} = 210$  nm,  $\lambda_{em} = 370$  nm).

# IR analysis of fluoride binding to compounds 7 and 8

The cymantrene based Lewis acid 7 (14 mg, 0.033 mmol) was dissolved in dry, degassed CDCl<sub>3</sub>, and the <sup>11</sup>B NMR ( $\delta_B$  30.4) and solution IR spectra measured [ $v_{CO}$  = 2025 cm<sup>-1</sup> (symmetric), 1945 cm<sup>-1</sup> (br, asymmetric)]. A slight excess of potassium fluoride (3 mg, 0.052 mmol) and 18-crown-6 (14 mg, 0.052 mmol) were added to the solution under argon, at which point the <sup>11</sup>B NMR ( $\delta_B$  6.7) of the reaction mixture indicated complete conversion to the fluoride adduct. The solution IR spectrum was measured again, also under inert atmosphere conditions, revealing a shift in the CO stretching frequencies:  $v_{CO} = 2007$  cm<sup>-1</sup> (symmetric), 1924 cm<sup>-1</sup> (br, asymmetric). An analogous procedure was employed for **8**, this time using [<sup>*n*</sup>Bu<sub>4</sub>N]F as the fluoride source. To a solution of **8** [18 mg, 0.056 mmol,  $\delta_B$  30.9,  $v_{CO} = 2028$  cm<sup>-1</sup> (symmetric), 1959 cm<sup>-1</sup> (br, asymmetric)] in CDCl<sub>3</sub> was added tetra-*n*-butylammonium fluoride hydrate (18 mg, 0.07 mmol), under anaerobic conditions. The <sup>11</sup>B NMR spectrum indicated a fluoride adduct by the upfield shifted resonance at

 $\delta_{\rm B}$  8.2, and the solution IR spectrum of the reaction displayed CO stretching frequencies at v<sub>CO</sub> = 2009 cm<sup>-1</sup> (symmetric), 1923 cm<sup>-1</sup> (br, asymmetric).

#### 4.3 Results and discussion

## 4.3.1 Fluoride binding by bis(boronate) ferrocene-based Lewis acids

Mindful of the specific anion binding properties displayed by ferroceneboronic acid with respect to fluoride,<sup>4,5</sup> and the possibility of anion chelation to give a stronger interaction between host/guest species,<sup>8,9,13</sup> fluoride binding studies were carried out involving the bifunctional boryl receptors **1a**, **2a**, **3a**, **4a** and **5a**. Initial anion binding experiments were carried out under inert atmosphere due to the air sensitivity of the catechol based Lewis acids, and the potential sensitivity of any fluoride adduct reaction products. The process of fluoride coordination to the various Lewis acid systems, *via* anion chelation or otherwise, was initially monitored by <sup>1</sup>H, <sup>11</sup>B and <sup>19</sup>F NMR.

For the case of compound **1a**, reaction with excess quantities of fluoride, either as ["Bu<sub>4</sub>N]F or KF in the presence of 18-crown-6 in CHCl<sub>3</sub> or DCM solution under anaerobic conditions, leads to an upfield shift of *ca*. 25 ppm from the free Lewis acid ( $\delta_B$  34.0) to a single broad resonance at  $\delta_B$  9.4. This shift in the <sup>11</sup>B signal is wholly consistent with the binding of an anionic donor to a three-coordinate boron centre. The <sup>19</sup>F NMR signal resulting from fluoride treatment ( $\delta_F$  -133.7), supports the successful complexation of F<sup>-</sup>, since the chemical shift observed is markedly different to ["Bu<sub>4</sub>N]F itself ( $\delta_F$  -122.7). The <sup>19</sup>F resonance also appears somewhat broadened in comparison to the fluoride source, presumably as a result of coupling to <sup>11</sup>B. Changes in the <sup>1</sup>H NMR spectrum upon fluoride treatment are apparent as slight broadening of Cp and boronic ester resonances from the parent compound, together with a small up-field shift of the respective resonances. No analogous changes in the <sup>1</sup>H and <sup>11</sup>B NMR spectra were observed upon the addition of large excesses (>20 equivalents) of Cl<sup>-</sup>, Br<sup>-</sup>, I<sup>-</sup>, BF<sub>4</sub><sup>-</sup>, PF<sub>6</sub><sup>-</sup>, H<sub>2</sub>PO<sub>4</sub><sup>-</sup>, HSO<sub>4</sub><sup>-</sup> or NO<sub>3</sub><sup>-</sup>, indicating that the binding process is selective for fluoride, as found for ferroceneboronic acid.<sup>4,5</sup>

As witnessed in the <sup>1</sup>H, <sup>11</sup>B and <sup>19</sup>F NMR, this fluoride binding behaviour is also observed for other bifunctional Lewis acids such as 2a, 3a, 4a and 5a. Once again, treatment of a chloroform solution of the respective bis-borylferrocene with ["Bu<sub>4</sub>N]F under anaerobic conditions results in a similar upfield shift in the <sup>11</sup>B NMR signal (approximately 25 ppm) as seen for compound 1a. The <sup>19</sup>F chemical shifts range from  $\delta_F$  128-135 as expected, by analogy with 1a.

From this NMR data, it can be concluded that some form of Lewis acidfluoride interaction does take place, however, determination of the mode of coordination requires further investigation. At this stage, it appears that three modes of fluoride coordination are feasible, as illustrated in Figure 4.6. Anion binding may take place *via* anion chelation in a bidentate fashion [Fig. 4.6 (i)], or monodentate coordination may take place in which the anion is fluxional between the two-boron centres, *i.e.* (ii). Alternatively, complexation of two fluoride ions; one to each boron may be more favourable, *i.e.* (iii).



Figure 4.6 Possible modes of coordination of F<sup>-</sup> to Lewis acids 1a, 2a, 3a, 4a, 5a: (i) anion chelation, (ii) monodentate but fluxional, (iii) bis(monodentate) binding.

A more in depth analysis of the shift in the <sup>11</sup>B NMR on F<sup>-</sup> coordination allows a determination of the likely mode of fluoride coordination to be made. On F<sup>-</sup> coordination to **1a**, a chemical shift change of 24.6 ppm is observed. An analogous system with which this shift change can be compared is the coordination of OH<sup>-</sup> by phenyl boronic acid, PhB(OH)<sub>2</sub>,<sup>18</sup> illustrated in Figure 4.7.



Figure 4.7 Hydroxide complexation by phenylboronic acid.

Phenyl boronic acid has a similar boron chemical environment and similar <sup>11</sup>B chemical shift to compounds **1a-5a**, possessing a three-coordinate boron centre, with

two oxygen substituents, linked to an aromatic  $\pi$ -system. The chemical shift change on anion binding for Ph(OH)<sub>2</sub> is 25.2ppm. If F<sup>-</sup> binding to the ferrocenyl Lewis acids occurs *via* anion chelation [Figure 4.6(i)] or the monodentate binding of 2 x F<sup>-</sup> ions (iii), then both boron centres transform from trigonal to pseudo-tetrahedral/tetrahedral geometry. Thus a chemical shift change similar to that observed for PhB(OH)<sub>2</sub> on coordination of OH<sup>-</sup> (i.e. 25ppm) would be expected, which is in agreement with the <sup>11</sup>B NMR data observed. If, on the other hand, F<sup>-</sup> binds in a monodentate fashion which is fluxional, then either two <sup>11</sup>B signals will be observed (slow exchange), or (more likely) a single signal representing the average chemical shift of three and fourcoordinate boron centres would be expected. In this fast exchange scenario, the signal would be an average of that expected for three and four-coordinate boron. Consequently, a shift on anion coordination approximately half that observed for PhB(OH)<sub>2</sub> (*i.e.* ~13 ppm) should result, thus making the monodentate fluxional scenario unlikely [Figure 4.6(ii)].

Further insight as to the actual mode of coordination has been provided by anaerobic <sup>1</sup>H NMR titration experiments involving the bis-borylferrocene **1a**. In the <sup>1</sup>H NMR spectrum of **1a**, the CH methine protons of the cyclic boronate provide a distinct singlet, the position of which has already been found to shift upfield on formation of the fluoride adduct. The chemical shift of these methine protons is therefore easily monitored as a function of added ["Bu<sub>4</sub>N]F, and hence allows plots of chemical shift vs. fluoride concentration to be constructed. The response of the methine proton resonance to the addition of successive aliquots of solid ["Bu<sub>4</sub>N]F is shown in Figure 4.8.



Figure 4.8 Plot of chemical shift ( $\delta_{\rm H}$ ) vs. concentration of fluoride, for the methine protons of the cyclic boronate fragment of 1a.

Implicit in the static, fluoride bound structure is inequivalence of the methine protons. However, the fact that they appear to remain equivalent throughout the titration experiment is consistent with rapid F<sup>-</sup> complexation/decomplexation kinetics on the NMR timescale. This was also found to be the case in the binding of benzylamine by (R,R)- $(Ph_2C_2H_2O_2B)_2C_6H_4$ , a similar bidentate receptor studied by Takaya *et. al.*<sup>19</sup>

Analysis of the resulting plot of chemical shift against fluoride concentration tends to indicate that the bifunctional Lewis acid 1a actually binds two equivalents of F<sup>-</sup>, one to each boron centre as portrayed in Figure 4.6 (iii). Most importantly; the initial form of the dependance of  $\delta_{\rm H}$  on fluoride concentration ([F<sup>-</sup>] < 0.08 mol dm<sup>-3</sup>) can be fitted to a quadratic expression ( $R^2 = 0.9949$ ). This not only implies the binding of two equivalents of fluoride, but also yields two complexation constants for the successive binding of one and two F<sup>-</sup> ions:  $K_1 = 4.1 \text{ mol}^{-1} \text{ dm}^3$ ,  $K_2 = 9.8 \text{ mol}^{-1} \text{ dm}^3$ .

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Binding of fluoride is therefore clearly weak, although comparable with the similar bidentate receptor as investigated by Takaya and co-workers in the binding of benzylamine  $(K_1K_2 = 18.8 \text{ mol}^{-2} \text{ dm}^6)$ .<sup>19</sup> This weak binding as indicated by the fluoride complexation constants is certainly an important factor in explaining the selectivity that Lewis acid **1a** possesses for fluoride, *i.e.* if fluoride is bound only weakly then other, less strongly coordinating anions are not likely to interact to any appreciable extent.

It can be concluded therefore that the mode of action of the fluoride binding process by the bifunctional Lewis acids 1a, 2a, 3a, 4a and 5a involves the selective binding of two equivalents of fluoride rather than anion chelation, as illustrated in Figure 4.6 (iii). <sup>1</sup>H NMR titration experiments with ["Bu<sub>4</sub>N]F were not performed for 2a, 3a, 4a or 5a due to the lack of a suitable (singlet) <sup>1</sup>H NMR handle. However, given the F<sup>-</sup> binding results implied by similar <sup>11</sup>B and <sup>19</sup>F NMR spectra, it is conceivable that the same mode of fluoride coordination applies to the whole series of bis-borylferrocenes when treated with  $\geq 2$  equivalents of ["Bu<sub>4</sub>N]F.

Fluoride binding experiments under aerobic conditions were also performed with the air-stable compound **1a**. In this case, attempts to carry out <sup>1</sup>H NMR titration experiments were inhibited by significant broadening of the relevant resonances, leading to unreliable data. Moreover, under aerobic conditions, treatment of a chloroform or dichloromethane solution of **1a** with an excess ( $\geq$ 2 equivalents) of fluoride, either as the tetra-*n*-butylammonium salt or as the potassium salt with 18-crown-6 is found to lead to a colour change from orange to green, shown pictorially in Figure 4.9.

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Figure 4.9 The colour change observed on addition of fluoride to a chloroform solution of 1a, under aerobic conditions.

By contrast, no colour change is found to take place if the same experiment is performed under anaerobic conditions, or if an alternative anion is used instead of fluoride (Cl<sup>-</sup>, Br<sup>-</sup>, I<sup>-</sup>, BF<sub>4</sub><sup>-</sup>, PF<sub>6</sub><sup>-</sup>, H<sub>2</sub>PO<sub>4</sub><sup>-</sup>, HSO<sub>4</sub><sup>-</sup> or NO<sub>3</sub><sup>-</sup>). UV/Vis spectroscopy provides a convenient means of monitoring the orange to green colour change. For the bis-borylferrocene **1a**, the UV/Vis spectrum in the absence of fluoride reveals bands characteristic of **1a** at 341 and 449 nm, in CHCl<sub>3</sub> solution. These bands are quantitatively replaced by new features at 428 nm and 629 nm upon the addition of two equivalents of solid [<sup>n</sup>Bu<sub>4</sub>N]F (Figure 4.10). Ferrocene itself displays no significant absorptions above 530 nm, whereas the oxidised form, the ferrocenium cation, displays absorptions attributable to a  ${}^{2}E_{2g} \rightarrow {}^{2}E_{1u}$  LMCT process at 617 nm.<sup>20</sup>



Figure 4.10 UV/Vis spectra of 1a (purple trace), and 1a *plus*  $\geq$ 2 equivalents of ["Bu<sub>4</sub>N]F (blue trace) in chloroform solution.

The band at 629 nm is therefore indicative of a ferrocenium type species, presumably formed by oxidation of the Lewis acid 1a by atmospheric oxygen on complexation of two equivalents of fluoride. Compound 5a undergoes a similar oxidation process on  $F^-$  binding, as judged from the UV/Vis spectra. Prior to addition of [<sup>n</sup>Bu<sub>4</sub>N]F in CHCl<sub>3</sub>, absorptions at 335 and 447 nm are observed, characteristic of the free Lewis acid 5a; subsequently these are replaced by features at 425 and 625 nm on  $F^-$  binding.

## 4.3.2 Monitoring of fluoride binding to 5a by fluorescence spectroscopy

Several research groups have previously utilised fluorescence spectroscopy as a means to follow the process of fluoride complexation by receptor species containing fluorescent chromophore functions.<sup>7,9,10</sup> The typical response of fluorescence quenching upon anion complexation makes it possible to not only to detect anions, but also to monitor the extent of host-guest interaction, for example, by fluorescence titration experiments. The napthalene moiety in particular is known to be an effective fluorescent chromophore as a result of  $\pi \rightarrow \pi^*$  transitions, allowing clear and distinct spectra to be obtained. Thus, fluorescence emission spectra of 1-(2-napthyl)-1,2ethanediol (napthalene-diol, the parent-diol of 5a), and the napthylene-containing receptor 5a were measured, as were spectra of 5a in the presence of fluoride ([<sup>n</sup>Bu<sub>4</sub>N]F). For comparison, the emission spectra of napthalene-diol (blue trace) and 5a (red trace) are shown in Figure 4.11, demonstrating clearly the effect of the attached boryl-ferrocene framework on the fluorescence intensity of the napthalene moiety.



Figure 4.11 Fluorescence emission spectra of napthalene-diol (5 x 10<sup>-4</sup> M, blue trace), and 5a (0.02 M, red trace) in MeCN solution.

The change in fluorescence spectra between the parent napthalene-diol and the bi-napthalene containing bis-borylferrocene is characterised by a shift in the emission spectral wavelength from  $\lambda_{em} = 330$  nm to  $\lambda_{em} = 370$  nm for 5a. More importantly,

however, is the significant reduction in fluorescence intensity of the napthalene moiety upon attachment to the borylferrocene framework. The extent of the quenching effect is somewhat surprising given the increased concentration of 5a compared to the parent-diol, and the fact that there are two napthyl groups per molecule in 5a. However, the napthyl groups attached to the cyclic boronate still provide more than sufficient fluorescence intensity to follow fluoride-binding events by fluorescence spectroscopy. The effect on the fluorescence of the addition of excess fluoride (as ["Bu<sub>4</sub>N]F) to a solution of 5a in acetonitrile, over a period of 12 hours is illustrated by Figure 4.12.



Figure 4.12 Change in fluorescence spectrum of 5a (0.02 M in MeCN) without F (black trace), and with addition of excess F<sup>-</sup>, after 15 min.(blue trace), 30 min.(pale blue trace), 1 h (green trace), and 5 h (red trace).

The addition of fluoride to the bis-borylferrocene 5a causes significant quenching of the fluorescence intensity of the napthyl group of 5a, as evident in Figure 4.12. This result is in agreement with the data obtained from the NMR and

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UV/Vis spectroscopic analysis of fluoride binding to such receptors, since it is well established that the binding of anions to Lewis acidic boron can result in the quenching of fluorescence of directly attached fluorophores. Furthermore, it appears likely that the effect of aerobic oxidation of the bis-fluoride adduct (as seen from UV/Vis spectroscopy and the naked eye) also plays a part in the quenching of fluorescence intensity. One might expect a gradual decay of fluorescence over time as seen in Figure 4.12, due to progressive oxidation. It appears likely therefore that the substantial quenching of fluorescence upon fluoride treatment of **5a** is caused by two contributing factors.

# 4.3.3 Electrochemical analysis of fluoride binding by bis-borylferrocenes

In the same way that cyclic voltammetry (CV) was used to analyse the electronic effect of the boryl moieties in compounds **1a-5a** (Chapter Three therein), CV was also employed to monitor the process of fluoride binding by these systems. The effect of this process on the oxidation potential of the ferrocene moiety has already been well demonstrated in the electrochemical detection of fluoride by ferroceneboronic acid by Shinkai.<sup>4</sup> Thus, CV has been shown to be a useful technique for analysing the electronic changes that take place at boron when F<sup>-</sup> coordination takes place. Analyses were performed in dry, degassed dichloromethane or acetonitrile by adding a small aliquot of ["Bu<sub>4</sub>N]F to the electrochemical cell following CV scan acquisition of the free compound. The cyclic voltammogram for the bis-boronic ester **1a** (blue trace), and **1a** plus an excess quantity of ["Bu<sub>4</sub>N]F (red trace) is illustrated in Figure 4.13; the corresponding electrochemical data for all bifunctional Lewis acids **1a-5a** before and after F<sup>-</sup> treatment is summarised in Table

4.1.



Figure 4.13 Cyclic Voltammogram of 1a (blue trace) and 1a  $plus \ge 2$ equivalents of ["Bu<sub>4</sub>N]F (red trace) in MeCN with ["Bu<sub>4</sub>N]PF<sub>6</sub> (0.1 M) as supporting electrolyte. Scan rate = 100 mV/s.

**Table 4.1** Electrochemical data of bis-borylferrocene systems 1a-5a with F<sup>-</sup> treatment {[<sup>n</sup>Bu<sub>4</sub>N]F}, [<sup>n</sup>Bu<sub>4</sub>N]PF<sub>6</sub> (0.1 M) as supporting electrolyte.

Compound	Solvent	Initial $E_{1/2}$ Relative to FcH ( $E_{1/2}$ Ref) (mV) <sup>a</sup>	F <sup>-</sup> adduct E <sub>1/2</sub> Relative to FcH (E <sub>1/2</sub> Ref.) (mV) <sup>a</sup>	Shift in E <sub>1/2</sub> (mV)
1a	DCM	+206	-746	-952
1a	MeCN	+222	-750	-972
2a	MeCN	+92	-598	-690
3a	DCM	+294	-716	-1010
<b>4</b> a	MeCN	+59	-593	-652
5a	DCM	+219	-518	-737

The cyclic voltammogram of Lewis acid 1a when treated with a source of fluoride is characterised by a relatively large negative shift in oxidation potential from the free compound (1a, Fig. 4.13, blue CV trace) to the fluoride adduct (1a plus  $\geq 2$ equivalents of ["Bu<sub>4</sub>N]F, Fig. 4.13, red trace). This shift in oxidation potential of ca. 1 V on the complexation of two fluoride ions is common in both dichloromethane and acetonitrile solution, indicating that the bis-fluoride adduct is significantly more easy to oxidise than the parent receptor. This result is probably best explained in terms of the electronic changes that take place at the boron centres on F<sup>-</sup> addition. Prior to anion coordination, both boryl moieties are net-electron acceptors, however, this effect is essentially reversed on binding of the anion to the extent that the boryl groups are transformed to net-electron donors. The ferrocene fragment consequently becomes relatively electron rich and as a result is much easier oxidised. A similar observation was made by the group of Piers, in which the binding of the Lewis base PMe<sub>3</sub> to  $FcB(C_6F_5)_2$  was characterised by a -550 mV shift in oxidation potential from the parent Lewis acid.<sup>21</sup> The relatively larger cathodic shift observed upon F<sup>-</sup> binding by 1a can be attributed to the fact that there are two such Lewis base (F)-Lewis acid binding processes taking place. In combination with this, the binding of two anions creates an overall double negative charge on the molecule; such that the ease with which it is possible to remove an electron is greatly enhanced, and is reflected in the oxidation potential for the bis-fluoride adduct being approximately -750 mV relative to ferrocene itself. In comparison with CV studies carried out by Shinkai et. al. in the electrochemical detection of fluoride by ferroceneboronic acid,<sup>4</sup> the corresponding oxidation potential shift changes are reported as <100 mV when binding of a single F<sup>-</sup> ion occurs in methanol/H2O mixtures or aqueous solution alone. The same process in DCM or MeCN with 1a is therefore markedly different with respect to the changes of

oxidation potential, perhaps due to a combination of solvent effects, together with the difference in binding two anions (-2 charge) compared with a single fluoride ion. Other features of interest in the CV experiment of **1a** plus ~2 equivalents of [<sup>n</sup>Bu<sub>4</sub>N]F in MeCN, include the presence of a quasi-reversible oxidation process at -318 mV (Fig. 4.13, red CV trace), this additional feature can be attributed to the oxidation of the *mono*-fluoride adduct of **1a**, which would be expected to occur at a less negative potential compared with the bis-fluoride adduct. Electrochemical experiments involving F<sup>-</sup> binding to the mono-borylferrocene system **1b** support this inference, given the oxidation potential of the mono-fluoride adduct, **1b**·F<sup>-</sup> (-378 mV w.r.t FcH/[FcH]<sup>+</sup> in MeCN, see Section 4.3.5).

The bis-borylferrocene systems 2a, 3a, 4a and 5a demonstrate similar behaviour when treated with ["Bu<sub>4</sub>N]F. Relative to the ferrocene/ferrocinium couple, oxidation of the parent Lewis acid occurs at the oxidation potentials listed in Chapter Three. These are shifted cathodically on  $F^-$  addition by approximately 0.6 V for 2a and 4a (in acetonitrile), and by *ca.* 1 V and 0.74 V for compounds 3a and 5a respectively in dichloromethane. A similar electrochemical shift on anion binding is therefore observed for all of the bifunctional Lewis acids, indicating that the addition of excess fluoride to a solution of the respective bis-borylferrocene renders the iron centre much easier to oxidise to the extent that atmospheric oxygen can generate the corresponding ferrocenium species. With the exception of the  $F^-$  adduct of 5a being quasi-reversible, in all cases 1a-4a, the reversible nature of the ferrocene component is maintained in forming the fluoride adduct, such that peak-peak separations are comparable with the anion-free receptors. Furthermore, the  $F^-$  binding by bis-boronic ester 1a with an alternative source of fluoride, as KF in the presence of 18-crown-6

also results in formation of the anionic adduct from NMR, an observation that is also reproduced in the electrochemistry of **1a** and **3a** with KF/18-C-6.

To conclude, it can therefore be shown that the mode of action of the bifunctional receptors in fluoride ion sensing involves: (i) the selective binding of two equivalents of fluoride; (ii) a cathodic shift of the oxidation potential of the iron centre in the presence of fluoride; and (iii) an orange to green colour change arising from the generation of a ferrocenium-based final product by aerobic oxidation of the bis-fluoride adduct (not observed under anaerobic conditions). These inferences appear consistent with the chemistry outlined in Scheme 4.4, in which the proposed formulation of the anionic adduct is shown.



Scheme 4.4 The proposed mechanism of fluoride ion sensing by bis(boryl)ferrocene receptors 1a-5a.

# 4.3.4 Fluoride binding by mono(boronate) ferrocene-based Lewis acids

Given the fluoride binding capabilities of the 1,1'-bis-boronic ester derivatives of ferrocene, such as **1a** and **2a**, it was of interest to determine whether monofunctional analogues such as **1b** and **2b** would display a similar response towards treatment with F<sup>-</sup>. With just a single boryl moiety in these cases, one would expect the binding of a single anion, if coordination is to take place at all. In any case, using NMR, UV/Vis and cyclic voltammetry to follow any fluoride binding, it should prove possible to analyse any differences in the electronic effects and oxidation chemistry of the mono-boryl Lewis acids both compared to bifunctional systems and to the parent ferroceneboronic acid.

As observed for its bis(boronate) counterpart (1a) and the related ferroceneboronic acid,<sup>4</sup> Lewis acid 1b is shown from <sup>1</sup>H, <sup>11</sup>B and <sup>19</sup>F studies to bind fluoride selectively under anaerobic conditions. The <sup>11</sup>B spectrum displays the typical response expected from conversion of a three-cordinate boron centre to four coordinate. The chemical shift of the free compound ( $\delta_B$  34.1), is shifted upfield by exactly 25 ppm to  $\delta_B$  9.1, in a similar fashion to 1a. The mono-catecholate boronic ester 2b also reacts in a similar fashion on addition of excess ["Bu<sub>4</sub>N]F to a chloroform solution of the Lewis acid, evident in the <sup>11</sup>B NMR from the common upfield shift of ~25 ppm. For both 1b and 2b, the <sup>19</sup>F NMR of the products following treatment with ["Bu<sub>4</sub>N]F indicate the presence of bound fluoride ( $\delta_F$  –136 and –128.5 ppm respectively). In addition, the process of F<sup>-</sup> binding to both 1b and 2b is manifested by a small shift and slight broadening of resonances in the <sup>1</sup>H NMR spectra. However, no such response in either <sup>1</sup>H or <sup>11</sup>B NMR spectra is witnessed for the alternative anions that were tested with the bifunctional systems.

Having established that a significant B-F interaction does take place to effect anion binding in systems 1b and 2b, the extent of the interaction and mode of binding was further probed by 'H NMR titration of 1b with fluoride as its tetra-nbutylammonium salt. As in the case of the bis-boryl species 1a, Lewis acid 1b also possesses the ideal <sup>1</sup>H NMR handle of a distinct singlet from the methine protons of the cyclic boronate backbone. Monitoring of the chemical shift of this resonance as a function of added fluoride leads to the generation of the analogous plot for 1b (Figure 4.14).



Figure 4.14 Plot of chemical shift ( $\delta_{\rm H}$ ) vs. concentration of fluoride, for the methine protons of the cyclic boronate fragment of 1b.

The plot of chemical shift vs. concentration of fluoride illustrated above for F<sup>-</sup> coordination to mono-boryl Lewis acid 1b confirms the binding of one equivalent of fluoride with a complexation constant of  $K = 5.0 \text{ mol}^{-1} \text{ dm}^{-3}$ . From the <sup>1</sup>H NMR data obtained, little (if any) further chemical shift change is observed on the addition of >1equivalent of ["Bu<sub>4</sub>N]F; a result that is mirrored in the <sup>11</sup>B NMR analysis by complete conversion of the free compound to the fluoride adduct on treatment with  $\geq 1$ equivalent of the anion. The binding of a single equivalent of fluoride by 1b under

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inert atmosphere appears to take place with a similar binding constant to that observed for the first fluoride bound to **1a**. As is the case for the bidentate analogues, it appears that this weak binding of fluoride ( $K = 5.0 \text{ mol}^{-1} \text{ dm}^3$ ) is what dictates the selectivity for fluoride over a range of alternative anions.

However, the binding of fluoride to mono-functional species 1b and 2b under *aerobic* conditions reveals a different (null) colorimetric response to that seen for the bis-boronic ester derivatives 1a-5a. Treatment of a chloroform solution of 1b or 2b in air with excess [<sup>n</sup>Bu<sub>4</sub>N]F is *not* accompanied by a colour change from orange to green, instead the reaction mixture remains orange-yellow in colour, decomposing slowly to a brownish residue over a period of ~48 hours. As a result, the UV/Vis analysis of compounds 1b and 2b display no bands characteristic of ferrocenium-type species (~617 nm)<sup>20</sup> on fluoride treatment. The proposed chemistry is therefore summarised in Scheme 4.5, indicating formation of the mono-fluoride adduct, which is not susceptible to aerobic oxidation to give a ferrocenium end-product.



Scheme 4.5 The proposed mode of action of fluoride ion binding by monoborylferrocene receptors 1b and 2b.

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#### 4.3.5 Electrochemical analysis of fluoride binding by mono-borylferrocenes

The use of cyclic voltammetry in analysing the fluoride binding process by the bis-borylferrocenes **1a-5a** has already provided an explanation for the oxidative chemistry that takes place when binding occurs in air. Thus, CV may also be employed to answer why such behaviour is not replicated in the mono-functional species **1b** and **2b** under similar conditions. Electrochemical measurements were performed in both dichloromethane and acetonitrile for **1b**, and in acetonitrile for **2b**, with solid [<sup>*n*</sup>Bu<sub>4</sub>N]F addition following acquisition of the CV scan of the free compound. In addition, analogous electrochemistry was also carried out for the parent ferroceneboronic acid in dichloromethane. The CV scans for **1b** (blue CV trace) and **1b** *plus*  $\geq$ 1 equivalent of F<sup>+</sup> (red trace) are depicted in Figure 4.15, with the corresponding results listed for all mono-boryl systems in Table 4.2.



Figure 4.15 Cyclic Voltammogram of 1b (blue trace) and 1b  $plus \ge 1$  equivalent of  $[^{n}Bu_{4}N]F$  (red trace) in DCM with  $[^{n}Bu_{4}N]PF_{6}(0.1 \text{ M})$  as supporting electrolyte. Scan rate = 100 mV/s.

<b>(able 4.2</b> Electrochemical data of mono-borylferrocene systems 1b, 2b, and
ferroceneboronic acid with F <sup>-</sup> treatment {["Bu <sub>4</sub> N]F}, ["Bu <sub>4</sub> N]PF <sub>6</sub> (0.1 M) as
supporting electrolyte.

Compound	Solvent	Initial E <sub>1/2</sub> Relative to FcH (E <sub>1/2</sub> Ref) (mV) <sup>a</sup>	F <sup>-</sup> adduct E <sub>1/2</sub> Relative to FcH (E <sub>1/2</sub> Ref.) (mV) <sup>a</sup>	Shift in E <sub>1/2</sub> (mV) <sup>a</sup>
16	DCM	+131	-403	-534
1b	MeCN	+116	-378	-494
2b	MeCN	+86	-304	-390
FcB(OH) <sub>2</sub>	DCM	+59	-342	-401

<sup>a</sup> FcH vs S.C.E:  $E_{1/2} = 0.46$  V (DCM), 0.40 V(MeCN)

The effect of fluoride on the oxidation potential of Lewis acid **1b** is illustrated clearly in Fig. 4.15 by a shift to a more negative potential (blue to red CV trace). This cathodic shift is consistent with the binding of fluoride, since on coordination the ferrocene moiety becomes relatively electron rich and the electron withdrawing effect of the boryl group is essentially cancelled out.

Of particular interest is the magnitude of the cathodic shift between the free compound 1b and the mono-fluoride adduct, compared to the equivalent experiment involving the bis-boronic ester 1a. On the addition of fluoride to the electrochemical cell, the oxidation potential of 1b undergoes a shift of approximately -0.5 V, a value which is about half of that seen for the bifunctional analogue 1a on fluoride treatment (*ca.* 1 V). Such a difference is expected given the electron withdrawing effect of only one boryl group on the ferrocene moiety, compared with two such features in 1a. In addition, the resultant mono-fluoride adduct possesses only a single negative charge, which is understandably more difficult to oxidise (*i.e.* is shifted to less negative

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potentials) than the bis-fluoride adduct  $[1a \cdot 2F]^{2^-}$ . The oxidation potential of -378 mV (in acetonitrile) for the adduct  $[1b \cdot F]^-$  also supports the assignment of a similar feature to a mono-fluoride adduct of receptor 1a, *i.e.*  $[1a \cdot F]^-$ , which is apparent in Figure 4.13 as a reversible feature with comparable oxidation potential (-318 mV, in acetonitrile).

In any case, both fluoride adducts of receptors **1b** and **2b** are significantly more easily oxidised than ferrocene itself (by -378 and -304 mV respectively in acetonitrile), attributed to the formation of the negatively charged adduct bearing an overall electron donating  $-B(OR)_2 \cdot F^-$  moiety. The bis(pentafluorophenyl)boryl ferrocene species, FcB(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub> reported by Piers and co-workers undergoes analogous electrochemical behaviour with respect to the binding of PMe<sub>3</sub>.<sup>21</sup> Although the boryl moiety is undoubtedly more Lewis acidic than those discussed herein, the overall shift in oxidation potential of -550 mV on binding in trifluorotoluene is comparable with that of **1b** and **2b** with fluoride.

A final important comparison can be made between **1b** and **2b** and ferroceneboronic acid.<sup>4,5</sup> Hence, using a minor adjustment of the method as reported by Floris and Illuminati,<sup>22</sup> ferroceneboronic acid was synthesised as an orange crystalline solid, and characterised by <sup>1</sup>H, <sup>13</sup>C and <sup>11</sup>B NMR spectra in agreement with those reported previously. In addition, single crystals have since been obtained enabling X-ray diffraction studies to be carried out.<sup>23</sup> The X-ray crystal structure (which was previously unpublished) is illustrated in Figure 4.16, and Figure 4.17, the latter displaying the packing of molecules in the solid state. Tables 4.3 and 4.4 list geometric parameters of interest.

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Figure 4.16 Molecular structure of  $(\eta^5-C_5H_5)Fe[\eta^5-C_5H_4B(OH)_2]$ , FcB(OH)<sub>2</sub>. ORTEP ellipsoids set at the 30% probability level; hydrogen atoms (except those attached to O1 and O2) omitted for clarity.

Table 4.3 Bond	distances (Å)	and angles (°)	for FcB(OH) <sub>2</sub> .

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Fe(1)-C(6)	2.020(4)	Fe(1)-C(1)	2.054(3)
Fe(1)-C(10)	2.032(4)	Fe(1)-C(8)	2.056(4)
Fe(1)-C(7)	2.039(4)	C(1)-B(1)	1.551(5)
Fe(1)-C(5)	2.043(3)	B(1)-O(2)	1.375(4)
Fe(1)-C(4)	2.047(4)	B(1)-O(1)	1.376(4)
Fe(1)-C(3)	2.048(3)	O(1)-H(1)	0.84
Fe(1)-C(2)	2.049(3)	O(2)-H(2a)	0.84
O(2)-B(1)-O(1)	118.0(3)	O(1)-B(1)-C(1)	123.9(3)
O(2)-B(1)-C(1)	118.1(3)		

D-H···A	<i>D</i> -Н	HA	D···A	<i>D-</i> H··· <i>A</i>
$O(1)-H(1)-O(2)^{i}$	0.84	2.14	2.930(3)	156
$O(2)-H(2a)-O(1)^{ii}$	0.84	1.97	2.806(3)	172

Table 4.4 Hydrogen bond distances (Å) and angles (°) for FcB(OH)<sub>2</sub>.

Symmetry codes: (i)  $\frac{1}{2} + x$ ,  $-\frac{1}{2} - y$ , z; (ii) -x, -1 - y, -1 - z.



Figure 4.17 A packing diagram of the solid state structure of  $FcB(OH)_2$  showing the hydrogen bonding motifs within and between  $[FcB(OH)_2]_2$  dimeric units. Distances are in Å.

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The solid state structure of FcB(OH)<sub>2</sub>, portrayed in Figure 4.16 displays structural parameters very similar to those observed in related compounds.<sup>23,24,25</sup> In particular, the geometries found at the Fe and B centre in FcB(OH)<sub>2</sub> are very similar to the corresponding bond distances and angles found in the solid state structures of 1,1'-ferrocenediboronic acid, as reported by Braga et. al.,<sup>24</sup> and the cyclic boronic anhydride (FcBO)<sub>3</sub>.<sup>25</sup> In comparison with the mono-boronic esters 1b and 2b, B-C(Cp) and B-O bond distances are comparable in all three cases, however, the O-B-O bond angle for  $FcB(OH)_2$  is distinctly larger (ca. 5°) presumably resulting from the lack of a cyclic boronate backbone tethering the oxygen atoms. The angles surrounding boron are therefore more characteristic of trigonal planar symmetry In the solid state, the molecular units of FcB(OH)<sub>2</sub> aggregate into (~120°). centrosymmetric dimers [FcB(OH)<sub>2</sub>]<sub>2</sub>, formed from two complementary O-H...O hydrogen bonding interactions of distance 1.97Å (Fig. 4.17). The eight-membered ring so formed is very similar to that seen in the crystal structures of 1,1'ferrocenediboronic acid<sup>24</sup> and phenylboronic acid, PhB(OH)<sub>2</sub>.<sup>26</sup> Further hydrogen bonding serves to link adjacent dimeric units utilising the remaining two oxygenbound H atoms per [FcB(OH)<sub>2</sub>]<sub>2</sub> moiety. This form of criss-cross dimeric linking is also observed in the solid state structure of the diboronic acid of ferrocene.<sup>24</sup>

Electrochemical experiments involving ferroceneboronic acid with fluoride treatment in dichloromethane have emphasised the effect of the solvent in providing large shifts in oxidation potential resembling those seen for both mono- and bifunctional Lewis acid systems with fluoride addition. An analogous electrochemical study reported by Shinkai and co-workers was performed in aqueous/methanol mixtures or in water, and yielded cathodic shifts of <100 mV on addition of  $F^-$  to the solution of FcB(OH)<sub>2</sub>.<sup>4</sup> The same experiment in dichloromethane

yields a cathodic shift in oxidation potential position of -401 mV. This result for FcB(OH)<sub>2</sub> in dichloromethane is comparable with those measured for the monoboronic esters **1b** and **2b**, and suggests that solvent effects are indeed significant in determining the oxidation potentials of the species under analysis.

In conclusion, it appears that the presence of a single boryl moiety, and therefore the binding of a single fluoride ion, as in the cases of **1b**, **2b** and  $FcB(OH)_2$ , is not sufficient to effect a colorimetric response to the coordination of fluoride. The electrochemical results confirm that the binding of fluoride to these monoborylferrocenes does *not* shift the oxidation potential to an extent by which atmospheric oxygen can oxidise the anionic adducts. Consequently, it would appear that only for bifunctional boronates (which bind two fluorides to give a dianion) is the electrochemical shift engendered by fluoride binding sufficient to bring about aerobic oxidation. Although monofunctional species bind fluoride with similar binding constants, the binding of a single fluoride does not shift the ferrocene-based oxidation sufficiently, hence no colour change is observed (Scheme 4.5).

#### 4.3.5 Fluoride binding by mono-borylcymantrene Lewis acids

Cp-pendant boronic esters based on cyclopentadienyl manganese tricarbonyl, cymantrene (7 and 8), offer the potential of monitoring of the anion binding process *via* infra-red spectroscopy. The carbonyl stretching frequencies (symmetric and asymmetric) of the cymantrene fragment have already been shown to differ between the parent compound CpMn(CO)<sub>3</sub> and the borylated derivatives 7 and 8 (Chapter Three). The presence of the boronic ester moiety gives rise to CO stretching frequencies at higher wavenumber. Given the fluoride binding properties observed for the mono-borylated ferrocenyl Lewis acids 1b and 2b, the analogous systems

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based on cymantrene might also effect fluoride recognition, allowing analysis by IR as well as NMR methods.

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The air sensitive nature of Lewis acids 7 and 8 mean that anion binding was best carried out under anaerobic conditions. Confirmation of fluoride binding to the borylcymantrenes 7 and 8 is apparent from their <sup>11</sup>B NMR spectra. On treatment of compound 7 ( $\delta_B = 31$ ) with  $\geq 1$  equivalent of [<sup>n</sup>Bu<sub>4</sub>N]F in dry CDCl<sub>3</sub>, complete conversion to the mono-fluoride adduct is observed as a 25 ppm upfield shift to  $\delta_{\rm B} 6.4$ . Similarly, under the same conditions, fluoride binding to Lewis acid 8 ( $\delta_B$  30.9) is characterised by a ca. 23 ppm shift upfield. Both results are highly indicative of formation of a tetra-coordinate fluoride adduct from a three-coordinate boryl moiety, as witnessed for the mono- and bis-boronic ester derivatives of ferrocene, in which binding was also confirmed by <sup>1</sup>H NMR titration and electrochemical methods. The <sup>19</sup>F NMR spectra are also in agreement with the inferences provided by <sup>11</sup>B NMR; shifts of  $\delta_{\rm F}$  = -135.6 and -130.2 for 7 and 8 respectively are comparable with the fluoride adducts of 1b and 2b. <sup>1</sup>H NMR analysis serves to authenticate the fluoride binding process, with Cp and boronic ester resonances being shifted and slightly broadened in the presence of F<sup>-</sup>, and no indication of decomposition being observed under an inert atmosphere.

The analysis of fluoride complexation by solution IR spectroscopy demonstrates clearly the changes in electron density that take place at the metal centre on binding. These are evident in the CO stretching frequencies that shift to markedly lower wavenumber upon anion coordination. The CO stretching frequencies for 7 are 2025 cm<sup>-1</sup> and 1945 cm<sup>-1</sup>. Addition of  $\geq$ 1 equivalent of fluoride yields complete conversion to the anionic adduct (confirmed by <sup>11</sup>B NMR), and results in shifts to lower wavenumber in the CO stretching frequencies (2007 cm<sup>-1</sup> and 1924 cm<sup>-1</sup>).

These shifts to lower wavenumber (in this case  $\sim 20 \text{ cm}^{-1}$ ) are consistent with the changes in electron density that one might expect on complexation of the anion.

Cymantrene-based Lewis acid **8** gives similar results from solution IR spectroscopy. In this case, carbonyl-stretching modes are shifted from 2028 cm<sup>-1</sup> and 1959 cm<sup>-1</sup> to 2009 cm<sup>1</sup> and 1923 cm<sup>-1</sup> respectively. The results obtained from both NMR and IR techniques for both 7 and 8 are consistent with the chemistry outlined in Scheme 4.6.



Scheme 4.6 Fluoride ion binding by mono-borylcymantrene receptors 7 and 8.

#### 4.4 Conclusions and suggestions for further research

Spectroscopic and electrochemical measurements on the bis-boronic ester derivatives of ferrocene, 1a-5a, have demonstrated selective binding of fluoride over a range of alternative anions. Thus, compound 1a is found to bind two equivalents of fluoride, which under aerobic conditions leads to oxidation to a ferrocenium-type chromophore. The resulting orange to green colorimetric response provides a means of detecting fluoride such that 1a (and 5a) is a redox-based fluoride ion sensor.<sup>3</sup> The catecholate bis(boronate) ester systems also display this behaviour, although the airsensitivity of the free compounds limits their potential as  $F^-$  as reliable colorimetric sensors.

Similarly, the mono-boryl derivatives of ferrocene are also specific towards fluoride binding, demonstrating similar binding constants for the complexation of a single fluoride ion. However, although the binding of a single  $F^-$  ion to form the singly negative charged adduct does render the ferrocene component easier to oxidise, the magnitude of this shift (as revealed by electrochemical measurements) is not sufficient to allow oxidation by atmospheric oxygen.

Although attempts to characterise the anionic adducts *via* X-ray diffraction methods have proved unsuccessful, the evidence presented herein appears sufficient to confirm the action of successful fluoride binding. In conclusion therefore, it appears that the lack of colorimetric response to fluoride treatment of mono-borylated ferrocene systems such as **1b** and **2b** are limited by their redox chemistry, and hence that sensor properties are dependent on the number of boryl moeties present.

Alternative systems such as those based on cymantrene, 7 and 8, have allowed further analysis of the electronic changes that occur upon anion complexation, by IR spectroscopy. In these cases, anion complexation at boron is accompanied by a redistribution of electron density towards the metal centre from the borylated Cp ligand, to the extent that  $\pi$  back-bonding between the carbonyl ligands and the manganese centre is increased.

Bearing these initial results towards fluoride binding by mono- and bifunctional boryl-metallocenes, further understanding may be achieved by analysing anion binding, particularly fluoride binding, by multifunctional boronic ester systems (tris- and tetra-borylferrocenes), since these are accessible *via* similar chemistry to that alluded to in Chapter Three.

The development of receptors capable of selectively binding alternative anions, such as cyanide, for example, would prove hugely advantageous with respect

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to poison sensing. The metallocene-based systems capable of selective fluoride sensing described herein have provided a potential starting point from which the sensing of other anions may be achievable. This may be possible by altering the substituents surrounding boron, thus tuning the Lewis acidity of the boron-based receptor towards the binding of specific anionic/Lewis basic targets.

## 4.5 References for Chapter Four

- "Host Guest Complex Chemistry I"; Vögtle, F., Ed.; Springer-Verlag: New York, 1981.
- See, for examples: P.D. Beer, Acc. Chem. Res., 1998, 31, 2, 71-80; P. D. Beer,
  P. A. Gale, G. Z. Chen, Coordination Chem. Rev., 1999, 185-186, 3-36; J. W.
  Steed and J. L. Atwood, in Supramolecular Chemistry, Wiley, New York, 2000,
  pp 198-249.
- 3. S. Aldridge, C. Bresner, I. A. Fallis, S. J. Coles, M. B. Hursthouse, Chem. Commun., 2002, 740.
- See, for example: C. Dusemund, K. R. A. Samankumara Sandanayake, S. Shinkai, J. Chem. Soc., Chem. Commun., 1995, 333; H. Yamamoto, A. Ori, K. Ueda, C. Dusemund, S. Shinkai, Chem. Commun., 1996, 407.
- 5. H. E. Katz, J. Am. Chem. Soc., 1986, 108, 7640.
- 6. S. Solé, F. P. Gabbaï, Chem. Commun., 2004, 1284.
- 7. S. Yamaguchi, S. Akiyama, K. Tamao, J. Am. Chem. Soc., 2001, 123, 11372.
- S. Yamaguchi, T. Shirasaka, S. Akiyama, K. Tamao, J. Am. Chem. Soc., 2002, 124, 8816.
- S. Arimori, M. G. Davidson, T. M. Fyles, T. G. Hibbert, T. D. James, G. I. Kociok-Köhn, Chem. Commun., 2004, 1640.
- 10. C. R. Cooper, N. Spencer, T. D. James, Chem. Commun., 1998, 1365.
- 11. S. Camiolo, P. A. Gale, Chem. Commun., 2000, 1129.
- M. Shionoya, H. Furuta, V. Lynch, A. Harriman, J. L. Sessler, J. Am. Chem. Soc., 1992, 114, 5714.
- 13. H. E. Katz, J. Org. Chem., 1985, 50, 5027.

- B. Dietrich, J. M. Lehn, J. Guilhem, C. Pascard, *Tetrahedron Lett.*, 1989, 30, 31, 4125.
- 15. W. B. Farnham, D. C. Roe, D. A. Dixon, J. C. Calebrese, R. L. Harlow, J. Am. Chem. Soc., 1990, 112, 7707.
- S. D. Reilly, G. R. K. Khalsa, D. K. Ford, J. R. Brainard, B. P. Hay, P. H. Smith, Inorg. Chem., 1995, 34, 569.
- 17. M. J. Hynes, J. Chem. Soc., Dalton Trans., 1993, 311.
- H. Nöth, B. Wrackmeyer, in Nuclear Magnetic Resonance Spectroscopy of Boron Compounds, Springer-Verlag: Berlin, Heidelberg, New York, 1978, pp. 140.
- K. Nozaki, M. Yoshida, H. Takaya, Angew. Chem., Int. Ed. Engl., 1994, 33, 2453.
- A. B. P. Lever, in *Inorganic Electronic Spectroscopy*, Elsevier, Amsterdam, 2<sup>nd</sup> edn., 1984, pp. 659-671.
- 21. B. E. Carpenter, W. E. Piers, M. Parvez, G. P. A. Yap, S. J. Rettig, Can. J. Chem., 2001, 79, 857.
- 22. B. Floris, G. Illuminati, J. Organomet. Chem, 1978, 150, 101.
- 23. C. Bresner et. al., Acta Cryst., 2004, E60, 1-3 and references cited therein.
- D. Braga, M. Polito, M. Bracaccini, D. D'Addario, E. Tagliavini, L. Sturba, F. Grepioni, Organometallics, 2003, 22, 2142.
- 25. J. W. Bats, K. Ma, M. Wagner, Act. Cryst., 2002, C58, m129-m132.
- 26. S. J. Rettig, J. Trotter, Can. J. Chem., 1977, 55, 3071.

# **Chapter Five**

# Hydrogen Fluoride Detection by Mixed Lewis Acid/Lewis Base Systems

#### 5.1 Introduction

The significance of anion recognition and fluoride recognition in particular is already well established within the literature, such that it has been the focus of considerable research effort (see Chapter Four and references therein). Reasons for this interest include the crucial roles played by such species in biological and environmental processes. Furthermore, the hydrolysis of chemical warfare agents such as sarin (GB) has been shown to yield fluoride or hydrogen fluoride by-products.<sup>1</sup> Mindful of these recent discoveries, and the current state of world affairs, the development of selective hydrogen fluoride sensors appears to be a fundamental chemical challenge. Many sensors for fluoride and other anions currently exist, however, few such systems are yet available for the detection of gaseous HF, which in addition to its relevance in the detection of chemical weapons, is itself an industrially valuable yet highly toxic substance.

Although reports of molecular compounds that can detect gaseous HF are largely unknown, ferrocene-based systems have been reported in the literature that could find potential application in hydrogen fluoride sensing. These compounds generally possess both Lewis acidic boron centres (for F<sup>-</sup> coordination), together with Lewis basic components (for H<sup>+</sup> coordination). Early reports by Marr, Moore and Rockett<sup>2</sup> described the synthesis of a 1,2-disubstituted ferrocene incorporating a pendant Lewis acidic boronic acid group with a neighbouring tertiary amine function (Scheme 5.1, I).



Scheme 5.1 Synthesis of 2-(*N*, *N*-Dimethylaminomethyl)ferroceneboronic acid I, as reported by Marr *et. al.* 

Later studies by Ori and Shinkai,<sup>3</sup> performed on a chiral ferrocenylboronic acid (Figure 5.1, II) similar to that reported by Marr *et. al.* revealed diastereoselective lithiation  $\alpha$  to the pendant amine function. The inclusion of a pendant nitrogen-donor functional group adjacent to the boronic acid moiety serves to facilitate the formation of cyclic esters with linear saccharides at neutral pH. Ferroceneboronic acid itself has also been shown to bind saccharides,<sup>4</sup> but only under strongly alkaline conditions. In the case of chiral dimethylaminoethyl pendant donors, selective binding of certain linear saccharides was observed leading to chiral discrimination of sugars (Scheme 5.2). Detection was achieved by electrochemical means, with chiral discrimination being largely confined to the linear, non-cyclic saccharides.



Scheme 5.2 Chiral discrimination of saccharides via electrochemical detection.

The chemistry of these amine-containing ferroceneboronic acids was further elaborated by Norrild and Søtofte.<sup>5-7</sup> In the first instance, reports concentrated on the structural assignment by NMR spectroscopy of a complex formed between sorbitol and the chiral ferroceneboronic acid **II**, investigated by Shinkai's group (Figure 5.1).<sup>3,5</sup> Another aim of this study was to determine whether an intramolecular B-N bond was formed on the reaction of sorbitol with the boronic acid. In the event, no such interaction was found to exist.



Figure 5.1 Structure of (S,S)-2-(N,N-dimethyl-1-aminoethyl)ferroceneboronic acid II, investigated by the groups of Shinkai and Norrild.

Π

Further work from the same group concentrated on the crystal structure analysis of I (Scheme 5.1), and the chiral ferroceneboronic acid II (Fig. 5.1), together with their derivatives formed by reaction with either benzopinacol or pinane-1,2,-diol.<sup>6</sup> The crystal structures of these species again ruled out the formation of a B-N bond. The formation of an intramolecular N-B bond was thought to be important in the binding of diols at neutral pH, since the equilibrium is shifted in favour of the cyclic boronate when the boron centre is close to four coordinate (Scheme 5.2). A more recent attempt to synthesise boronic acid-based glucose sensors was carried out by the same group,<sup>7</sup> involving the synthesis of novel ferrocene-based systems for electrochemical detection (Figure 5.2).



Figure 5.2 Novel boronic acids synthesised by Norrild and Søtofte.

For the mono-boronic acid III (Fig. 5.2) the crystal structure obtained from complexation with cyclotriboroxane incorporates a B-N interaction, thought to strongly enhance carbohydrate binding at physiological pH. With respect to glucose binding, <sup>13</sup>C-NMR revealed promising results in the case of all ferrocene-based boronic acids III, IV and V; although it was concluded that further evidence concerning the structures of such adducts was required.

A related approach has also been reported recently by the group of James *et*. *al.*<sup>8</sup> Compound VI, illustrated in Figure 5.3 has been shown to display interesting electrochemical saccharide sensing capabilities. This diboronic acid allows control of saccharide selectivity through two-point binding, with enhanced binding for Dglucose and D-galactose indicated by stability constant measurements.





Very recently, Barba and co-workers have published a synthetic study of intramolecular base-stabilised ferrocenyl boronates.<sup>9</sup> The reactions of ferroceneboronic acid with a range of tridentate ligands have been shown to yield both monomeric (VII) and dimeric ferrocenyl boronates (VIII), which are portrayed in Figure 5.4. In all cases, condensation reactions using Dean-Stark methods resulted in the formation of the respective B-O bonded cyclic boronates each featuring an intramolecular B-N bond.



Figure 5.4 Monomeric and dimeric ferrocenylboronates with B-N intramolecular base stabilisation.

Characterisation by X-ray diffraction and NMR spectroscopy confirmed the structures reported, and in particular the presence of a dative N-B bond. The overall aim of the study was to establish the electronic and steric factors involved in the formation of macrocyclic structures, and thus determine a route to new boron-containing macrocycles. In this case, the ferrocenyl moiety was employed due to its inherent bulk and electrophilicity, compared with phenyl, for example. It was concluded that these compounds could find potential applications in ferrocene-based molecular recognition, in addition to providing an insight to boron-based macrocyclic synthesis.

#### 5.1.1 Aims of the present research

Given our initial success in the detection of fluoride, and the potential uses for hydrogen fluoride sensors, it was decided to synthesise and probe the whole acid binding capabilities of ferrocene-based systems incorporating both Lewis acidic and Lewis basic functions. Such species offer the potential for binding the HF molecule either intact, or as discrete  $H^+$  and  $F^-$  entities. This might be accomplished, for example, by incorporation of a Lewis basic nitrogen centre for coordination to the hydrogen of HF, while maintaining the fluoride binding selectivity *via* Lewis acidic boronic ester or acid moieties (Scheme 5.3). Investigation of the selective binding of hydrogen fluoride is particularly difficult using gaseous HF due to its highly corrosive and toxic nature. However, using the hydrogen fluoride-collidine complex as a HF source, or separate sources of  $H^+$  and  $F^-$ , it should prove possible to follow the binding process by cyclic voltammetry and NMR techniques, as well as by X-ray diffraction.

Possible molecular architectures incorporating the necessary Lewis acidic and Lewis basic functions include 9a, 10a and 11a depicted in Scheme 5.3, featuring differing degrees of intramolecular B-N coordination.



11a (R = R' = H)

Scheme 5.3 Synthetic routes to potential mixed Lewis acid/Lewis base HF receptors.

# 5.2 Synthesis and characterisation of mixed Lewis acid/Lewis base receptors

# 5.2.1 Experimental

Synthesis of base-stabilised borylferrocene,  $FcB(OCH_2CH_2)_2NMe$ , 9a

To a solution of dibromoborylferrocene (1.45 g, 4.1 mmol) in dry toluene (200 cm<sup>3</sup>) at room temperature, was added dropwise (Me<sub>3</sub>SiOCH<sub>2</sub>CH<sub>2</sub>)<sub>2</sub>NMe (5 cm<sup>3</sup> of a 0.814 M solution in toluene, 4.1 mmol) further diluted in toluene (50 cm<sup>3</sup>). The

reaction mixture was stirred for 24 h, during which time the mixture turned from red to orange in colour. Following filtration *via* cannula, volatiles were removed *in vacuo*. The resulting residue was then redissolved in a sufficient volume of toluene for recrystallisation at -30°C, and isolated as an orange microcrystalline solid, yield 68%. Single crystals suitable for X-ray diffraction were grown by hexane diffusion into a toluene solution of **9a**. <sup>1</sup>H NMR ([D<sub>6</sub>]benzene, 300 MHz, 20 °C),  $\delta$  1.59 [s, 3H, CH<sub>3</sub>], 1.92 [br m, 4H, CH<sub>2</sub>], 3.64 [m, 2H, CH<sub>2</sub>], 3.73 [m, 2H, CH<sub>2</sub>], 4.34 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 4.39 [m, 2H, C<sub>5</sub>H<sub>4</sub>], 4.47 [s, 5H, C<sub>5</sub>H<sub>5</sub>]; <sup>13</sup>C NMR ([D<sub>6</sub>]benzene, 76 MHz, 20 °C),  $\delta$  46.4 [CH<sub>3</sub>], 59.9 [CH<sub>2</sub>], 61.7 [CH<sub>2</sub>], 68.9 [CH of C<sub>5</sub>H<sub>5</sub>], 69.7 [CH of C<sub>5</sub>H<sub>4</sub>], 72.6 [CH of C<sub>5</sub>H<sub>4</sub>]; <sup>11</sup>B NMR ([D<sub>6</sub>]benzene, 96 MHz, 20 °C),  $\delta$  13.4 (br). IR (KBr disc, cm<sup>-1</sup>), v = 2870 md, 1453 md, 1636 w, 1453 md, 1368 w, 1239 md, 1225 st, 1106 st, 1078 st, 999 st, 912 md, 852 md, 817 st, 724 md. UV/Vis (chloroform):  $\lambda_{max}$  ( $\epsilon$ ) 444 nm,  $\epsilon$  = 123.5 mol<sup>-1</sup>cm<sup>-1</sup>dm<sup>3</sup>. MS(EI): M<sup>+</sup> = 313 (80%), exact mass (calc.) 313.0931, (obs) 313.0932.

#### Synthesis of (1-piperidyl-2, 3-propanediolato)borylferrocene, 10a

The piperidine-diol precursor  $(C_5H_{10}N)CH_2CH(OH)CH(OH)$  (0.448 g, 2.81 mmol) was dried *in vacuo* for 12h, then dissolved in a toluene/THF mixture (*ca.* 50/100 cm<sup>3</sup>). The resulting solution was cooled to -78°C, and *n*-butyllithium (3.51 cm<sup>3</sup> of a 1.6 M solution, 5.6 mmol) added dropwise by syringe while stirring. The resulting solution was allowed to return to room temperature and stirred for a further 2 h. A solution of dibromoborylferrocene (1 g, 2.81 mmol) in toluene (50 cm<sup>3</sup>) was then transferred dropwise *via* cannula to the dilithiate mixture, with stirring at room temperature. After stirring for 24 h, cannula filtration of the cloudy reaction mixture yielded a clear orange filtrate and off-white residue. Removal of the toluene solvent *in vacuo* 

afforded an orange residue, which was subjected to further continuous pumping. The resulting orange solid was washed with hexanes (2 x 25 cm<sup>3</sup>), dried *in vacuo*, and redissolved in toluene from which the compound was recrystallised in pure form at -30°C (19 % yield). <sup>1</sup>H NMR ([D]chloroform, 400 MHz, 20°C)  $\delta$  1.4-2.8 [br m, 10H, all five CH<sub>2</sub>s of piperidyl group], 3.54 [m, 1H, BOCH], 3.87 [m, 2H, NCH<sub>2</sub>], 4.08 [s, 5H, C<sub>5</sub>H<sub>5</sub>], 4.11 [s, 2H, C<sub>5</sub>H<sub>4</sub>], 4.34 [m, 2H, BOCH<sub>2</sub>], 4.49 [m, 1H, C<sub>5</sub>H<sub>4</sub>], 4.61 [m, 1H, C<sub>5</sub>H<sub>4</sub>]; <sup>13</sup>C NMR ([D]chloroform, 76 MHz, 20°C),  $\delta$  22.9 [br, CH<sub>2</sub> of piperidyl group], 25.4 [br, CH<sub>2</sub>s of piperidyl group], 55.7 [br, NCH<sub>2</sub>s of piperidyl group], 56.7 [N-CH<sub>2</sub>], 68.7 [CH of C<sub>3</sub>H<sub>5</sub>], 68.8 [CH of C<sub>3</sub>H<sub>4</sub>], 72.4, 73.2 [CH of C<sub>3</sub>H<sub>4</sub>], 74.1, 74.4 [CH and CH<sub>2</sub> of cyclic boronate]; <sup>11</sup>B NMR ([D]chloroform, 96 MHz, 20°C),  $\delta$  32.3 (br). IR (KBr disc, cm<sup>-1</sup>), v = 3086 md, 2935 st, 1489 md, 1472 st, 1383 md, 1308 md, 1260 md, 1219 w, 1181 w, 1127 md, 1105 st, 1029 md, 806 md, 684 w. UV/Vis (chloroform):  $\lambda_{max}$  ( $\varepsilon$ ) 446 nm,  $\varepsilon$  = 248.3 mol<sup>-1</sup>cm<sup>-1</sup>dm<sup>3</sup>. MS(EI): M<sup>+</sup> = 353.1 (70%), exact mass (calc.) 353.1244, (obs) 353.1251.

#### Synthesis of (N,N-Dimethylaminomethyl)ferroceneboronic acid, 11a

11a was prepared by minor modification of the method published by Marr, Moore and Rockett.<sup>2</sup> (*N*,*N*-dimethylaminomethyl)ferrocene (2 g, 8.2 mmol) was dissolved in dry ether (50 cm<sup>3</sup>) under argon. The solution was cooled to 0°C and *n*-butyllithium (5.66 cm<sup>3</sup> of a 1.6M solution, 9.0 mmol) added dropwise. Stirring was continued for a further 1h at 0°C, after which the mixture was allowed to return to room temperature over 30 min. B(OMe)<sub>3</sub> (1.85 cm<sup>3</sup>, 16.5 mmol) was syringed into dry ether under argon and the resulting solution added dropwise by cannula to the lithiated mixture with stirring at -78°C. On complete addition, stirring was stopped and the reaction mixture allowed to stand overnight, slowly returning to room temperature.

Hydrolysis with water (50 cm<sup>3</sup>) at 0°C was carried out, the phases separated, and the aqueous phase extracted with ether (2 x 40 cm<sup>3</sup>). The combined organic phase was washed twice with brine (40 cm<sup>3</sup>), dried over MgSO<sub>4</sub> and the solvent removed by rotor evaporation. Addition of 40-60 petroleum ether (15 cm<sup>3</sup>) to the orange residue yielded an orange solid which was isolated and dried *in vacuo* to give the pure compound. A second batch was obtained by concentration and cooling of the supernatent solution to -30°C, resulting in an overall yield of 53%. <sup>1</sup>H and <sup>11</sup>B NMR spectra were in agreement with those previously reported.<sup>2</sup>

## Electrochemical analyses for compounds 9a, 10a, 11a

Electrochemical analyses were carried out in a common fashion. Electrolyte: 0.1 M ["Bu<sub>4</sub>N][PF<sub>6</sub>] acetonitrile; reference electrode standard: 0.1 M ["Bu<sub>4</sub>N][PF<sub>6</sub>], 0.01 M silver nitrate in acetonitrile. Following degassing of the electrolyte solution with argon, background cyclic voltammetry (CV) scans were measured and a small sample (< 1 mg) of the compound was added to the solution. Further degassing served to purge the solution of any additional dissolved oxygen and to dissolve the solid compound by agitation, prior to spectral acquisition.

### 5.2.2 Results and discussion

Intramolecular coordination of a tethered base has proved to be a particularly useful strategy in the stabilisation of a range of low coordinate main group compounds.<sup>9,10</sup> Thus amino-tin and -boron halides featuring tethered picolyl bases are readily accessible by reacting SnCl<sub>4</sub> or BBr<sub>3</sub> with trimethylsilyl substituted amine precursors. By using a similar approach, the preparation of the intramolecular nitrogen-base stabilised boryl-ferrocene **9a** can be accomplished in yields of up to

68 % from 1-dibromoboryl ferrocene<sup>11, 12</sup> and the *bis*(trimethylsilyl) ether derivative of *N*-methyldiethanolamine.  $(\eta^5-C_5H_5)Fe[\eta^5-C_5H_4B(OCH_2CH_2)_2NCH_3]$  (9a) is an airstable orange crystalline solid, which shows no sign of decomposition when stored under aerobic conditions, even for prolonged periods. Spectroscopic measurements (<sup>1</sup>H and <sup>13</sup>C NMR) are consistent with the proposed formulation, displaying the expected C5H5 singlet and mono-substituted C5H4 signature (inequivalent CHs in the 2- and 3-positions). Moreover, the methyl and methylene signals of the N-methyldiethanolamine unit are in evidence, being shifted from the corresponding signals for (Me<sub>3</sub>SiOCH<sub>2</sub>CH<sub>2</sub>)<sub>2</sub>NMe. The <sup>11</sup>B NMR spectrum supports the presence of a B-N donor acceptor interaction; the single resonance at  $\delta_{\rm B}$  13.4 is in the range expected for tetra-coordinate boron atoms containing a dative N-B bond.9,13 In addition to appropriate UV/Vis and IR spectra, the mass spectrum displays the molecular ion peak at m/z = 313, and a close match between theoretical and observed isotopic patterns. The structure of 9a is confirmed by the results of the single crystal X-ray diffraction study, illustrated in Figure 5.5. Single crystals were grown by slow hexane diffusion into a concentrated solution of the compound in toluene. Relevant

structural parameters are listed in Table 5.1.

The molecular structure of **9a** displays a crystallographically imposed plane of symmetry. This mirror plane passes through the atoms C(3), N(1), B(1), C(4), C(7) and Fe(1). Interesting features of the solid state structure of **9a** include the existence of a dative N-B bond, the length of which is 1.735(3)Å. This distance is somewhat longer than those observed in the crystal structures of the monomeric and dimeric ferrocenylboronates [Fig. 5.4 (i) and (ii)] reported by Barba and co-workers,<sup>9</sup> the bond lengths of which are typically in the order of 1.64Å.



Figure 5.5 Molecular structure of  $(\eta^5 - C_5H_5)Fe[\eta^5 - C_5H_4B(OCH_2CH_2)_2NMe]$  (9a). ORTEP ellipsoids set at the 30% probability level; hydrogen atoms omitted for clarity.

Fe(1)-C(7)	2.030(3)	N(1)-C(3)	1.462(4)
Fe(1)-C(4)	2.058(2)	N(1)-C(2)	1.486(2)
O(1)-B(1)	1.443(2)	O(1)-C(1)	1.404(2)
B(1)-C(4)	1.595(4)	C(1)-C(2)	1.512(3)
B(1)-N(1)	1.735(3)	C(7)-C(8)	1.410(3)
B(1)-O(1)-C(1)	112.21(17)	C(1)-C(2)-N(1)	106.01(17)
B(1)-O(1)-C(1) O(1)-B(1)-C(4)	112.21(17) 111.92(14)	C(1)-C(2)-N(1) C(2)-N(1)-C(3)	106.01(17) 110.40(15)
B(1)-O(1)-C(1) O(1)-B(1)-C(4) N(1)-B(1)-C(4)	112.21(17) 111.92(14) 114.3(2)	C(1)-C(2)-N(1) C(2)-N(1)-C(3) C(3)-N(1)-B(1)	106.01(17) 110.40(15) 116.7(2)
B(1)-O(1)-C(1) O(1)-B(1)-C(4) N(1)-B(1)-C(4) B(1)-C(4)-C(5)	112.21(17) 111.92(14) 114.3(2) 127.19(11)	C(1)-C(2)-N(1) C(2)-N(1)-C(3) C(3)-N(1)-B(1) O(1)-B(1)-N(1)	106.01(17) 110.40(15) 116.7(2) 99.80(14)

Table 5.1 Selected bond distances (Å) and angles (°) for 9a.

In addition, the intramolecularly base stabilised boron fluoride,  $FB(OCH_2CH_2)_2NMe$ , in which the ferrocene moiety of **9a** is formally replaced by an electronegative fluorine atom,<sup>10,13</sup> possesses a significantly shorter B-N bond of 1.622 Å. The boron-oxygen bond lengths in **9a** [1.443(2)Å] are very similar to those found in Barba's compounds [Fig.5.4 VII and VIII] but are significantly longer than those found in **2a** containing trigonal boron (~1.37Å), indicating that nitrogen-base stabilisation reduces the extent of  $\pi$ -electron donation from adjacent oxygen substituents.

An alternative approach to introducing a Lewis basic function into the borylferrocene is to synthesise a cyclic boronate using a pre-formed OCH<sub>2</sub>CH(R)O framework, in which for example,  $R = CH_2N(C_5H_{10})$ . The resulting five-membered cyclic boronate engenders increased rigidity and allows more facile chelation at

boron. The existence of a N-B interaction is also less likely due to the single carbon bridge between the cyclic boronate and the Lewis base, thus preventing the orientation required for such an interaction from being attained.

The piperidine-substituted cyclic boronate 10a is accessible as a crystalline orange solid in pure form, although yields are relatively low for the recrystallised product at only 19%. 10a is slightly air sensitive and is therefore best stored under inert atmosphere conditions. Spectroscopic characterisation by <sup>1</sup>H and <sup>13</sup>C NMR indicate the presence of both boryl-pendant C<sub>5</sub>H<sub>4</sub> and non-substituted C<sub>5</sub>H<sub>5</sub> ligands. The cyclic boronate and piperidine moieties also give rise to resonances in the expected region, however, the various signals are broadened significantly compared to the free diol, possibly due to restricted rotation in solution. The <sup>11</sup>B NMR spectrum of 10a features a broad singlet with a markedly dissimilar chemical shift at ( $\delta_{\rm B}$  32.3) compared to that of the base-stabilised species 9a ( $\delta_B$  13.4). This chemical shift is located in the region expected for three-coordinate dialkoxoboryl ferrocenes (c.f. 2aand 3a, Chapter Three, this thesis), suggesting that in this case, coordination of the lone pair of the piperidine-nitrogen to electron deficient boron does not occur, and that no dative N-B bond exists. This presumably reflects the fact that the piperidinenitrogen cannot orientate itself to form such an intramolecular bond, due to the restraints of the tethering hydrocarbon backbone. Alternatively, the boron atom may not be sufficiently Lewis acidic and/or the nitrogen sufficiently Lewis basic enough to effect a B-N interaction, although this seems unlikely given the structure of 9a. The results obtained from mass spectrometry experiments display the molecular ion peak at m/z = 353, and close agreement between theoretical and observed isotopic patterns, and in conjunction with UV/Vis and infrared data corroborate the proposed structure of 10a as depicted in Figure 5.6.



Figure 5.6 The proposed formulation of  $(\eta^5-C_5H_5)Fe[\eta^5-C_5H_4B(O_2CH_2CHCH_2NC_5H_{10})]$ , (10a).

#### 5.2.3 Electrochemistry of mixed Lewis acid/Lewis base receptors

Cyclic voltammetry has already proved useful in determining the electronic effect of Lewis acidic boryl groups linked to the ferrocene backbone (Chapter Three). Therefore, as a method of probing whether the presence of an intramolecular base has any effect on the oxidation potential of the ferrocene backbone, electrochemistry (CV) was also carried out on compounds 9a, 10a, and 11a. Cyclic voltammetry measurements were performed in acetonitrile solution using the standard set-up described in section 5.2.1, and with ferrocene as the reference compound. Figures 5.7, 5.8 and 5.9 illustrate the respective scans for compounds 9a, 10a and 11a, and the data obtained from these experiments is summarized in Table 5.2.



Figure 5.7 Cyclic Voltammogram of 9a in MeCN with  $[^{n}Bu_{4}N]PF_{6}(0.1 \text{ M})$  as supporting electrolyte. Scan rate = 100 mV/s.



Figure 5.8 Cyclic Voltammogram of 10a in MeCN with  $["Bu_4N]PF_6(0.1 \text{ M})$  as supporting electrolyte. Scan rate = 100 mV/s.

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Figure 5.9 Cyclic Voltammogram of 11a in MeCN with  $[^{n}Bu_{4}N]PF_{6}(0.1 \text{ M})$  as supporting electrolyte. Scan rate = 100 mV/s.

Table 5.2 Electrochemical data of mixed Lewis acid/Lewis base borylferrocenes, 9a,10a, 11a and ferroceneboronic acid (for comparative purposes) with ["Bu<sub>4</sub>N]PF<sub>6</sub>(0.1 M) as supporting electrolyte.

Compound	Solvent	Peak-Peak separation (Ep <sup>ox</sup> -Ep <sup>red</sup> ) (mV)	$E_{1/2}$ Relative to FcH (E <sub>1/2</sub> Ref.) (mV) <sup>a</sup>
9a	MeCN	85	-190.5
10a	MeCN	96	-0.5
11a	MeCN	85	+37.5
FcB(OH) <sub>2</sub>	DCM	85	+59

<sup>a</sup> FcH vs S.C.E:  $E_{1/2} = 0.46$  V (DCM), 0.40 V(MeCN)

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As indicated by their respective peak-peak separations [~59 mV and close to 80 mV for FcH (ref.)], the cyclic voltammograms of all three amine-containing borylferrocenes display typical FcH/[FcH]<sup>+</sup> electrochemical responses with a high degree of reversibility. Of interest are the relative potentials of these oxidation events with respect to each other, and with respect to ferrocene itself. The intramolecular basestabilised boryl system 9a displays an oxidation potential shifted cathodically (ca. -190 mV) relative to ferrocene. This observation suggests that 9a is easier to oxidise than ferrocene, as the dative N-B bond appears to convert the boryl moiety from what would be a net-electron withdrawing group (for a three-coordinate boryl system), into a net electron donor on nitrogen coordination. The analogous experiment with piperidine-containing compound 10a (Figure 5.8) resulted in an unexpected electrochemical response. The <sup>11</sup>B NMR data is consistent with the absence of any N-B interaction, and as a result the boron centre in this case is expected to be three-coordinate and therefore electron withdrawing with respect to the Cp ring. On this basis, and from the electrochemical experiments performed with the mono-borylferrocenes 2a and 3a (Chapter Three), it might be expected that oxidation of 10a should occur with a positive potential with respect to ferrocene. However, the electrochemical results demonstrate that oxidation occurs at a potential comparable to that of ferrocene (-0.5 mV w.r.t. FcH/[FcH]<sup>+</sup>). It is conceivable that a degree of intermolecular B-N association occurs for 10a in solution, although such an observation is difficult to rationalize given the measured <sup>11</sup>B NMR chemical shift. The electrochemistry of the base-containing ferroceneboronic acid 11a provides an interesting comparison with those of 9a and 10a. In this case, the Lewis basic component is no longer part of the boryl group and by analogy with the work of Norrild and Søtofte,<sup>6</sup> no N-B interaction is thought to occur. The cyclic voltammetry

measurements for **11a** show a reversible oxidation process at +37.5 mV relative to ferrocene. Of the three Lewis base-containing systems, it appears that **11a** is the only compound that is clearly more difficult to oxidise than the parent compound ferrocene. However, it is apparent that the Cp-pendant -CH<sub>2</sub>NMe<sub>2</sub> group does influence the FcH/[FcH]<sup>+</sup> oxidation potential somewhat. When compared to ferroceneboronic acid<sup>14,15</sup> (+59 mV w.r.t. FcH/[FcH]<sup>+</sup> in DCM), a slight electron donating effect for the -CH<sub>2</sub>NMe<sub>2</sub> group is revealed. Clearly however, the electron withdrawing effect of the Lewis acidic boryl moiety is greater than the donating effect of ferrocene itself.

#### 5.3 HF binding by mixed Lewis acid/Lewis base receptors

#### 5.3.1 Experimental

Reaction of mixed Lewis acid/Lewis base systems (9a, 10a, 11a) with collidine-HF

A common procedure was typically employed, exemplified here for **10a**. The respective ferrocenyl-Lewis acid/base compound (typically 30 mg, 0.085 mmol for **10a**) was dried *in vacuo* for 2 h, then dissolved in dry/degassed acetonitrile (*ca*. 20 cm<sup>3</sup>). Hydrogen fluoride-collidine complex (1 equivalent of HF, 8.6 mg, 0.06 mmol) was quickly added to the solution as a solid and the reaction mixture stirred for 20 min. The <sup>11</sup>B NMR spectrum of the reaction mixture at this point revealed the presence of both starting material ( $\delta_B$  33.2 for **10a**) and a minor product peak ( $\delta_B$  3.9, quartet). Another aliquot of the HF-collidine complex (representing a further 1 equivalent of HF, 9 mg, 0.06 mmol) was quickly added to the reaction mixture which was subsequently stirred for a further 20 min. The <sup>11</sup>B NMR now revealed the

product ( $\delta_B$  3.9 quartet) as the major resonance, with starting material still present. A final addition of HF-collidine complex (~1 further equivalent of HF, 10 mg, 0.066 mmol) resulted in the formation of a small quantity of yellow-orange precipitate. The <sup>11</sup>B NMR of the yellow supernatent solution now indicated complete conversion to the product ( $\delta_B$  3.8). Cannula filtration of the reaction mixture followed by cooling to -30°C yielded the respective products as orange-yellow crystalline solids, **9b**, **10b** and **11b**, in yields of 44%, 31% and 39% respectively (all unoptimised).

# Spectroscopic data for $[(\eta^5 - C_5H_5)Fe(\eta^5 - C_5H_4BF_3)]^{-1}[(HOCH_2CH_2)_2NH(CH_3)]^{+}$ , 9b, the product of the reaction of 9a with ~3 equivalents of HF

<sup>1</sup>H NMR ([D<sub>3</sub>]acetonitrile, 300 MHz, 20°C),  $\delta$  2.88 [s, 3H, NCH<sub>3</sub>], 3.26 [br m, 4H, NCH<sub>2</sub>], 3.50 [br s, 2H, OH], 3.81 [t, J = 5 Hz, 4H, CH<sub>2</sub>OH], 4.03 [s, 5H, C<sub>5</sub>H<sub>5</sub>], 4.08 [br m, 4H C<sub>5</sub>H<sub>4</sub>], 6.97 [v br s, 1H, NH<sup>+</sup>]; <sup>13</sup>C NMR ([D<sub>3</sub>]acetonitrile, 76 MHz, 20°C),  $\delta$  40.8 [NCH<sub>3</sub>], 55.1 [NCH<sub>2</sub>], 57.6 [CH<sub>2</sub>OH], 67.7 [br, CH of C<sub>5</sub>H<sub>5</sub>], 71.5 [br, CH of C<sub>5</sub>H<sub>4</sub>]; <sup>11</sup>B NMR ([D<sub>3</sub>]acetonitrile, 96 MHz, 20°C),  $\delta$  3.0 (q,  $J_{B-F} = 49.3$  Hz); <sup>19</sup>F NMR ([D<sub>3</sub>]acetonitrile, 283 MHz, 20°C),  $\delta$  –136.0 (q,  $J_{F-B} = 49.1$  Hz). IR (KBr disc, cm<sup>-1</sup>), v = 3437 st, 3146 md, 2965 st, 1468 w, 1443 w, 1373 w, 1337 w, 1262 st, 1227 md, 1101 st, 1056 st, 1016 st, 981 md, 850 md, 805 st. MS (Electrospray) ES+: [MeNH(CH<sub>2</sub>CH<sub>2</sub>OH)<sub>2</sub>]<sup>+</sup> = 120.2 (100%), exact mass (calc.) 120.1019, (obs) 120.1021; M<sup>+</sup>= {[FcBF<sub>3</sub>]<sup>-</sup>[(HOCH<sub>2</sub>CH<sub>2</sub>)<sub>2</sub>NHCH<sub>3</sub>]<sup>+</sup>}<sup>+</sup> = 371.1, [M-HF]<sup>+</sup>= 353.2, [M-2HF]<sup>+</sup>= 313.3 (all weak).

## Spectroscopic monitoring of reaction of 10a with HF (to form product 10b)

<sup>1</sup>H NMR ([D<sub>3</sub>]acetonitrile, 300 MHz, 20°C),  $\delta$  1.6-3.1 [v br m, 10H, all five CH<sub>2</sub>s of piperidyl group], 2.38 [s, 3H, CH<sub>3</sub> of collidine], 2.55 [s, 6H, CH<sub>3</sub> of collidine], 3.48

[br m, 2H, CH<sub>2</sub>OH], 3.51 [m, 1H, CHOH], 3.73 [m, 2H, NCH<sub>2</sub>], 3.99 [br m, 4H, C<sub>5</sub>H<sub>4</sub>], 4.04 [s, 5H, C<sub>5</sub>H<sub>5</sub>]; <sup>11</sup>B NMR ([D<sub>3</sub>]acetonitrile, 96MHz, 20°C),  $\delta$  3.2 (q, J<sub>B-F</sub> = 49.5 Hz); <sup>19</sup>F NMR ([D<sub>3</sub>]acetonitrile, 283MHz, 20°C),  $\delta$  –134.5 (q, J<sub>F-B</sub> = 48.9 Hz).

Spectroscopic data for  $\{(\eta^5-C_5H_5)Fe(\eta^5-C_5H_3[BF_3]^-[CH_2NH(CH_3)_2]^+\}$ , 11b, the product of the reaction of 11a with ~3 equivalents of HF

<sup>1</sup>H NMR ([D<sub>3</sub>]acetonitrile, 300 MHz, 20°C),  $\delta$  2.57 [s, 3H, NCH<sub>3</sub>], 2.83 [s, 3H, NCH<sub>3</sub>], 3.75 [d, J = 13 Hz, 1H, CH<sub>2</sub>N], 4.08 [s, 5H, C<sub>5</sub>H<sub>5</sub>], 4.15 [m, 3H, C<sub>5</sub>H<sub>3</sub>], 4.55 [d, J = 13 Hz, 1H, CH<sub>2</sub>N], 6.98 [v br s, 1H, NH<sup>+</sup>]; <sup>13</sup>C NMR ([D<sub>3</sub>]acetonitrile, 76 MHz, 20°C),  $\delta$  40.7 [N(CH<sub>3</sub>)], 43.3 [N(CH<sub>3</sub>)], 60.0 [CH<sub>2</sub>N], 68.4 [CH of C<sub>5</sub>H<sub>3</sub>], 68.7 [CH of C<sub>5</sub>H<sub>5</sub>], 70.6, 73.8 [CH of C<sub>5</sub>H<sub>3</sub>], 77.6 [quaternary *C*-CH<sub>2</sub>N of C<sub>5</sub>H<sub>3</sub>]; <sup>11</sup>B NMR ([D<sub>3</sub>]acetonitrile, 96 MHz, 20°C),  $\delta$  3.0 (q,  $J_{B-F} = 49.3$  Hz); <sup>19</sup>F NMR ([D<sub>3</sub>]acetonitrile, 283 MHz, 20°C),  $\delta$  -133.9 (q,  $J_{F-B} = 48.7$  Hz). IR (KBr disc, cm<sup>-1</sup>), v = 3174 st [NH], 1489 w, 1473 w, 1448 w, 1388 md, 1297 w, 1248 w, 1187 md, 1165 w, 1139 md, 1102 st, 1035 st, 1009 st, 946 st, 921 st, 890 md, 853 md, 813 st, 757 w. MS(EI): {Fc[BF<sub>3</sub>]<sup>-</sup>[CH<sub>2</sub>NH(CH<sub>3</sub>)<sub>2</sub>]<sup>+</sup>-HF}<sup>+</sup> = 291 (75%), exact mass (calc) 291.0683, (obs.) 291.0685, {Fc[BF<sub>3</sub>]<sup>-</sup>[CH<sub>2</sub>NH(CH<sub>3</sub>)<sub>2</sub>]<sup>+</sup>-HF-NMe<sub>2</sub>}<sup>+</sup> = 247 (100%), exact mass (calc.) 247.0185, (obs.) 247.0186. MS (Electrospray) ES+: {Fc[BF<sub>3</sub>]<sup>-</sup>[CH<sub>2</sub>NH(CH<sub>3</sub>)<sub>2</sub>]<sup>+</sup>-BF<sub>3</sub>}<sup>+</sup> = 242.9 (100%).

# Reaction of **9a** with HCl/["Bu<sub>4</sub>N]F

**9a** (63 mg, 0.2 mmol) was dried *in vacuo* for 2h, then dissolved in dry/degassed acetonitrile (*ca.* 30 cm<sup>3</sup>). A solution of dry HCl (0.2 cm<sup>3</sup> of a 1.0 M solution in ether, 0.2 mmol) was quickly added to the yellow solution and stirred for 20 min yielding a slight precipitate.<sup>\* 11</sup>B NMR of the supernatent solution at this point revealed a single

broad resonance at  $\delta_B$  30 ppm. ["Bu<sub>4</sub>N]F (1 equivalent, 53 mg, 0.2 mmol) was quickly added as a solid and stirred for 20 min. At this point, <sup>11</sup>B NMR of the reaction mixture revealed several resonances at  $\delta_B$  30.1, 12.2 and a multiplet at 3.8 ppm, while <sup>19</sup>F NMR indicated major peaks at -136 and -151 ppm. Further additions (1, 2 equivalents and excess) of ["Bu<sub>4</sub>N]F followed by stirring, resulted in the disappearance of the signals at  $\delta_B$  30 and 12 ppm and enhancement of the multiplet at  $\delta_B$  3.7 ppm (q,  $J_{B-F} = 49.8$  Hz),  $\delta_F$  -136 (q,  $J_{F-B} = 48.6$  Hz).

<sup>\*</sup> <sup>1</sup>H NMR of the precipitate indicated hydrolysis of the cyclic boronate upon HCl addition to form ferroceneboronic acid, FcB(OH)<sub>2</sub>.<sup>16</sup>

## Reaction of **11a** with $HCl/[^{n}Bu_{4}N]F$

**11a** (20 mg, 0.07 mmol) was dried *in vacuo* for 2 h, then dissolved in dry/degassed acetonitrile (*ca.* 15cm<sup>3</sup>). Dry HCl (0.07 cm<sup>3</sup> of a 1.0 M solution in ether, 0.07 mmol) was quickly added to the yellow solution *via* syringe and stirred for 20 min. <sup>11</sup>B NMR of the yellow solution a single resonance at  $\delta_B$  30.8 ppm. [<sup>*n*</sup>Bu<sub>4</sub>N]F (1 equivalent, 22 mg, 0.07 mmol) was quickly added as a solid, the mixture stirred for 15 min, and the <sup>11</sup>B NMR measured again showing a broad resonance at  $\delta_B$  30.1 ppm, and a quartet at 3.9 ppm. A further 2 equivalents of [<sup>*n*</sup>Bu<sub>4</sub>N]F (48 mg, 0.14 mmol) were added with stirring, however, <sup>11</sup>B NMR monitoring still showed a small amount of starting material present in addition to the product at 4.2 ppm. A final aliquot of [<sup>*n*</sup>Bu<sub>4</sub>N]F (15 mg, 0.048 mmol) was added, with <sup>11</sup>B NMR revealing complete conversion to a quartet at  $\delta_B$  4.25 ppm; the <sup>19</sup>F NMR spectrum indicated that the major product gave rise to a multiplet at  $\delta_F = -133$  ppm, with smaller minor signals at -135 and -138 ppm. [End product:  $\delta_B$  3.7 ppm (q,  $J_{B-F} = 49.5$  Hz),  $\delta_F -133.2$  (q,  $J_{F-B} = 48.2$  Hz)].
Electrochemical analyses for compounds 9a, 10a, 11a and their HF adducts 9b, 10b, 11b

Electrochemical analyses were carried out in a common fashion. Electrolyte: 0.1 M ["Bu<sub>4</sub>N][PF<sub>6</sub>] in acetonitrile; reference electrode standard: 0.1 M ["Bu<sub>4</sub>N][PF<sub>6</sub>], 0.01 M silver nitrate in acetonitrile. Following degassing of the electrolyte solution with argon, background cyclic voltammetry (CV) scans were measured and a small sample (<1 mg) of the HF receptor was added to the solution. Further degassing served to purge the solution of any additional dissolved oxygen and agitate the solid to dissolve the compound, prior to spectral acquisition. Further CV scans were measured on the addition of aliquots of solid HF-collidine complex, or on the addition of HCl (1.0M solution in ether), followed by fluoride (as ["Bu<sub>4</sub>N]F) once more. Ferrocene was later added as a reference compound. In the cases where the HF adducts were previously synthesised, a small aliquot of adduct was added to the solution following background scan acquisition, and the CV measured as described above.

#### 5.3.2 Results and discussion

The use of the commercially available hydrogen fluoride-collidine complex (or  $Et_3N\cdot 3HF$  etc) enables HF binding experiments to be carried out without having to resort to the gaseous form of hydrogen fluoride, which is itself highly corrosive and toxic. As a result, the binding of HF was attempted in solution with compounds **9a**, **10a** and **11a** using HF-collidine complex as a source of the acid.

The reaction of the intramolecularly base stabilised boryl-ferrocene 9a with collidine-HF yields an orange crystalline product (9b), soluble only in polar solvents such as acetonitrile. A characteristic feature of this reaction is that for complete

conversion to the HF adduct, at least three equivalents of the acid source are required as determined by <sup>11</sup>B NMR spectroscopy.

The <sup>1</sup>H and <sup>13</sup>C NMR spectra for 9b feature the characteristic signatures of both substituted  $(C_5H_4)$  and non-substituted  $(C_5H_5)$  cyclopentadienyl ligands. In addition, signals due to the B-(OCH<sub>2</sub>CH<sub>2</sub>)<sub>2</sub>-NCH<sub>3</sub> backbone are apparent, together with a very broad  $NH^+$  resonance which supports the formation of a  $H^+F^-$  adduct. The <sup>11</sup>B NMR signal of the product ( $\delta_B$  3.0 ppm) appears in the correct region for fourcoordinate boron,<sup>17,18</sup> which would result from the binding of the fluorine component of HF. However, the resonance appears clearly to be a quartet, implying that the boron centre is bonded to three fluorine atoms ( $^{19}$ F, I =  $\frac{1}{2}$ ), to give a tetra-coordinate Cp-BF<sub>3</sub><sup>-</sup> arrangement. This is the first indication that the addition of HF to the receptor 9a causes breakage of the B-O bonds to form a [FcBF<sub>3</sub>]<sup>-</sup> ionic species. The form of the resonance observed in the <sup>19</sup>F NMR spectrum ( $\delta_F = -136$ ) is in accordance with that expected for fluorine linked to one boron atom  $\binom{11}{11}B$ ,  $I = \frac{3}{2}$ ,  $\frac{19}{10}i.e.$  a 1:1:1:1 quartet with an identical coupling constant to that found in the <sup>11</sup>B NMR spectrum. Electrospray mass spectrometry experiments did not yield a molecular ion signal characteristic of a mono-HF adduct or the FcBF<sub>3</sub><sup>-</sup> fragment suggested from <sup>11</sup>B NMR. By contrast, the positive ion electrospray spectrum displayed a clear peak attributable to the  $[(HOCH_2CH_2)_2NH(CH_3)]^+$  ion. Furthermore, the molecular ion for the salt { $[FcBF_3][(HOCH_2CH_2)_2NHCH_3]$ } appears as a weak feature at m/z = 371, along with peaks corresponding to successive removal of one, two and three molecules of HF. The spectroscopic inferences obtained from multinuclear NMR, and electrospray mass spectrometry results are confirmed by single crystal X-ray diffraction studies, which solid **9**b reveal the state structure of to be the salt

 ${[FcBF_3]}^-$  [(HOCH<sub>2</sub>CH<sub>2</sub>)<sub>2</sub>NHCH<sub>3</sub>]<sup>+</sup>}, illustrated in Figure 5.10. Relevant bond lengths and angles are listed in Table 5.3.



**Figure 5.10** Molecular structure of  $[(\eta^5-C_5H_5)Fe(\eta^5-C_5H_4BF_3)]^-$ [(HOCH<sub>2</sub>CH<sub>2</sub>)<sub>2</sub>NH(CH<sub>3</sub>)]<sup>+</sup> (**9b**). ORTEP ellipsoids set at the 30% probability level; hydrogen atoms (except those attached to O1, O2 and N1) omitted for clarity.

Fe(1)-C(7)	2.039(3)	B(1)-F(3)	1.405(4)
Fe(1)-C(4)	2.024(3)	C(1)-C(2)	1.393(5)
C(9)-B(1)	1.590(4)	N(1)-C(11)	1.498(4)
B(1)-F(1)	1.435(3)	N(1)-C(12)	1.495(4)
B(1)-F(2)	1.423(3)	N(1)-H(1b)	0.9300
B(1)-C(9)-C(8)	127.2(2)	F(1)-B(1)-F(3)	106.1(2)
B(1)-C(9)-C(8) F(1)-B(1)-C(9)	127.2(2) 111.5(3)	F(1)-B(1)-F(3) F(2)-B(1)-F(3)	106.1(2) 107.0(3)
B(1)-C(9)-C(8) F(1)-B(1)-C(9) F(2)-B(1)-C(9)	127.2(2) 111.5(3) 112.6(2)	F(1)-B(1)-F(3) F(2)-B(1)-F(3) C(8)-C(9)-C(10)	106.1(2) 107.0(3) 105.7(2)
B(1)-C(9)-C(8) F(1)-B(1)-C(9) F(2)-B(1)-C(9) F(3)-B(1)-C(9)	127.2(2) 111.5(3) 112.6(2) 112.7(2)	F(1)-B(1)-F(3) F(2)-B(1)-F(3) C(8)-C(9)-C(10) C(11)-N(1)-C(12)	106.1(2) 107.0(3) 105.7(2) 110.7(2)

Table 5.3 Selected bond distances (Å) and angles (°) for 9b.

The solid state structure of **9b** clearly reveals the result of treatment of compound **9a** with the HF-collidine complex. Rather than resulting in the formation of an intact adduct, *i.e.*  $Fc[B(F)(OCH_2CH_2)_2NH(Me)]$ ; complete reaction with HF is only effected by the addition of 3 equivalents and causes cleavage of the dative boron-nitrogen and covalent boron-oxygen bonds, forming the oxygen and nitrogen-protonated *N*-methyldiethanolammonium cation and the ferrocenyltrifluoroborate anion, as an ion pair. The solid state structure of the  $[FcBF_3]^-$  fragment has previously been reported by Batey and co-workers as the tetra-*n*-butylammonium salt,<sup>20</sup> with which the structural parameters of **9b** are in close agreement. The boron-fluorine bond distances [1.405(4) Å, 1.423(3) Å and 1.435(3) Å] are also comparable with alternative fluoride sensor systems possessing B-F bonds, as reported by Tamao *et. al.*,<sup>21</sup> and Katz.<sup>22</sup>

Although no intramolecular hydrogen-bonding interactions are present within the asymmetric unit, there is a degree of intermolecular hydrogen-bonding which serves to link neighbouring asymmetric units, thus aiding packing of the units in the crystalline state. Hydrogen bonding interactions occur between H(1a) and the atom F(2) of an adjacent unit  $[O(1)-H(1a)\cdots F(2), O(1)\cdots F(2) = 2.747(3)Å, 160.8^{\circ}]$ , and between H(2a) and F(1)  $[O(2)-H(2a)\cdots F(1), O(2)\cdots F(1) = 2.690(2)Å, 176.7^{\circ}]$ ; the geometric parameters of which are within the expected range for the atoms involved.

From the above results, it appears clear that the intramolecularly basestabilised borylferrocene 9a is not an ideal candidate for the detection of hydrogen fluoride (certainly not in a reversible fashion), since HF treatment results in loss of the Lewis basic component required for coordination of the hydrogen of HF. As an alternative, it was decided to attempt whole acid HF binding using the piperidinecontaining borylferrocene 10a. The smaller five-membered cyclic boronate ring may constitute a more stable arrangement with respect to HF complexation, thus preventing breakage of the B-O ester bonds and loss of the Lewis basic amine moiety. An additional advantage of this system indicated from its spectroscopic characteristics, is that no dative N-B interaction exists. Thus, HF binding does not require breakage of an existing N-B interaction, therefore the complexation process should be energetically more favourable. The analogous reaction of compound 10a with collidine-HF in acetonitrile, however, appears to produce a response similar to that seen with 9a. Monitoring of the reaction by <sup>11</sup>B NMR, reveals that at least three equivalents of HF are required for complete conversion to the final product. The orange crystalline product resulting from treatment of 10a with excess quantities of HF-collidine complex exhibits limited solubility in polar solvents such as acetonitrile, suggesting possible salt formation as in 9b. Characterisation of the orange crystalline

product by <sup>1</sup>H, <sup>13</sup>C, <sup>11</sup>B and <sup>19</sup>F NMR is consistent with the formulation portrayed in Figure 5.11, involving B-O bond cleavage when the Lewis acid/base receptor is exposed to three equivalents of HF.



Figure 5.11 The proposed structure of  $[(\eta^5-C_5H_5)Fe(\eta^5-C_5H_4BF_3)]^-$ [HOCH<sub>2</sub>CH(OH)CH<sub>2</sub>(NHC<sub>5</sub>H<sub>10</sub>)]<sup>+</sup>, (10b).

Thus, inspection of the <sup>1</sup>H and <sup>13</sup>C NMR spectra reveal signals characteristic of a mono-substituted ferrocene system, in addition to resonances resulting from the cationic portion of the salt. It is the <sup>11</sup>B and <sup>19</sup>F NMR spectra, however, which yield the most significant evidence for the proposed ion pair formation of **10b**. In the <sup>11</sup>B spectrum, a virtually identical chemical shift ( $\delta_B$  3.2) is observed to that measured for the structurally characterised anionic component of **9b**. The same coupling pattern (quartet) and coupling constant of *ca*. *J* = 49 Hz are also seen, thus confirming the existence of one boron atom coupled to three-spin  $\frac{1}{2}$  <sup>19</sup>F nuclei. The <sup>19</sup>F spectrum is also identical to that observed for **9b**.

In conclusion, it appears that even the five-membered cyclic boronate is not sufficiently robust to withstand hydrolysis of the boron-oxygen bonds when treated with HF, as bond cleavage again results in formation of a  $[FcBF_3]^-$  salt, with loss of the Lewis basic amine residue.

In view of the above results it seems unlikely that mixed Lewis acid/base sensors involving linking B-O bonds will survive intact exposure to HF. It seems

logical therefore to attempt HF sensing with a system in which the Lewis acidic and Lewis basic sites are effectively independent of each other, yet within reasonably close proximity so that complete HF complexation can be attained. The literature compound (N,N-dimethylaminomethyl)ferroceneboronic acid (11a)initially synthesised by Marr, Moore and Rockett<sup>2</sup> is found to feature such attributes: Lewis acidic boryl and Lewis basic amine functionalities occupying adjacent positions on one cyclopentadienyl ligand. In addition, the C-B and C-N linkages should be stable to HF treatment, thus meaning that the overall molecular architecture should remain intact. The same reaction procedure for 11a with collidine-HF in acetonitrile solution was performed as for compounds 9a and 10a, and again yields an orange crystalline product 11b, soluble in only polar media. Analysis of the <sup>1</sup>H and <sup>13</sup>C spectroscopic data shows the existence of a bi-functionalised ferrocene backbone. The <sup>1</sup>H NMR spectrum of 11b indicates protonation of the Lewis basic nitrogen by the presence of a very broad signal at approximately 6.9 ppm; in addition the CH<sub>2</sub>N and N(CH<sub>3</sub>)<sub>2</sub> resonances appear shifted from the parent compound 11a. <sup>11</sup>B ( $\delta_B$  3.0, quartet) and <sup>19</sup>F NMR spectra ( $\delta_{\rm F}$  -134, quartet) display patterns consistent with the BF<sub>3</sub><sup>-</sup> moiety  $(J_{B-F} = 49 \text{ Hz})$ . The inferences suggested from the NMR data are not wholly supported by the mass spectrometry measurements, since a molecular ion of  $(\eta^5 C_5H_5$ )Fe[ $\eta^5$ -C<sub>5</sub>H<sub>3</sub>(BF<sub>3</sub>)(CH<sub>2</sub>NMe<sub>2</sub>H)] is not observed, although some potential fragmentation products of such a zwitterionic species are found. In particular, ions are observed corresponding to loss of an HF molecule from the parent species, and to loss of the BF<sub>3</sub><sup>-</sup> moiety. Although the mass spectrometry and NMR data appear to conflict, conclusive evidence of the structure of 11b is obtained crystallographically (see Figure 5.12 and Table 5.4). Single crystals of 11b were grown by cooling a concentrated acetonitrile solution of the reaction product to -30°C. Although the -OH

groups of the boronic acid are lost in the 3:1 reaction of **11a** with HF (presumably liberating two equivalents of H<sub>2</sub>O), the molecular structure shown in Figure 5.12(a) and Figure 5.12(b) displays an effectively intact HF-adduct,  $(\eta^5-C_5H_5)Fe[\eta^5-C_5H_3(BF_3)(CH_2NMe_2H)]$ .



Figure 5.12(a) Molecular structure of  $(\eta^5-C_5H_5)Fe\{\eta^5-C_5H_3(BF_3)[CH_2N(CH_3)_2H]\}$ (11b). ORTEP ellipsoids set at the 30% probability level; hydrogen atoms (except those attached to N1) omitted for clarity.



Figure 5.12(b) Dimerization of 11b in the solid state through pair-wise hydrogen bonding interactions. ORTEP ellipsoids set at the 30% probability level; hydrogen atoms (except that attached to N1) omitted for clarity.

Fe(1)-C(1)	2.062(3)	F(3)-H(1)	2.204
Fe(1)-C(2)	2.020(4)	F(3)-H(1)'	2.124
C(1)-B(1)	1.600(6)	N(1)-C(11)	1.527(4)
B(1)-F(1)	1.413(5)	N(1)-F(3)	2.996(4)
B(1)-F(2)	1.382(5)	N(1)-F(3)'	2.854(3)
B(1)-F(3)	1.431(5)	N(1)-H(1)	0.9300
B(1)-C(1)-C(2)	125.3(3)	F(1)-B(1)-F(3)	106.7(3)
B(1)-C(1)-C(2) B(1)-C(1)-C(5)	125.3(3) 129.2(3)	F(1)-B(1)-F(3) F(2)-B(1)-F(3)	106.7(3) 106.9(3)
B(1)-C(1)-C(2) B(1)-C(1)-C(5) F(1)-B(1)-C(1)	125.3(3) 129.2(3) 111.1(3)	F(1)-B(1)-F(3) F(2)-B(1)-F(3) C(2)-C(11)-N(1)	106.7(3) 106.9(3) 112.7(3)
B(1)-C(1)-C(2) B(1)-C(1)-C(5) F(1)-B(1)-C(1) F(2)-B(1)-C(1)	125.3(3) 129.2(3) 111.1(3) 115.5(3)	F(1)-B(1)-F(3) F(2)-B(1)-F(3) C(2)-C(11)-N(1) C(12)-N(1)-C(13)	106.7(3) 106.9(3) 112.7(3) 111.2(3)
B(1)-C(1)-C(2) B(1)-C(1)-C(5) F(1)-B(1)-C(1) F(2)-B(1)-C(1) F(3)-B(1)-C(1)	125.3(3) 129.2(3) 111.1(3) 115.5(3) 108.3(3)	F(1)-B(1)-F(3) F(2)-B(1)-F(3) C(2)-C(11)-N(1) C(12)-N(1)-C(13) F(3)'-H(1)-N(1)	106.7(3) 106.9(3) 112.7(3) 111.2(3) 134.44(18)
B(1)-C(1)-C(2) B(1)-C(1)-C(5) F(1)-B(1)-C(1) F(2)-B(1)-C(1) F(3)-B(1)-C(1) F(1)-B(1)-F(2)	125.3(3) 129.2(3) 111.1(3) 115.5(3) 108.3(3) 107.9(3)	F(1)-B(1)-F(3) F(2)-B(1)-F(3) C(2)-C(11)-N(1) C(12)-N(1)-C(13) F(3)'-H(1)-N(1) F(3)-H(1)-N(1)	106.7(3) 106.9(3) 112.7(3) 111.2(3) 134.44(18) 142.49(19)

Table 5.4 Selected bond distances (Å) and angles (°) for 11b.

The structure of zwitterionic 11b, indicates clearly the formation of an  $H-F/H^+F^-$  adduct in the solid state as an overall charge neutral complex, maintaining both boryl and amine-derived functions. With the exception of the Cp-pendant  $-CH_2NMe_2$  remaining attached to the ferrocene component, the molecular arrangement is very similar to that obtained from the reaction of the intramolecularly base-stabilsed system 9a with HF-collidine complex (Figure 5.10, 9b).

However, the most significant aspect of this structure is the geometry of the B-F…H-N fragment, and therefore the extent of bond rupture of the bound HF molecule. The residual intramolecular H…F interaction is relatively weak (as evidenced by a separation of 2.204 Å), being best viewed as a hydrogen bond between

the  $-BF_3^-$  and  $-NMe_2H^+$  fragments. In comparison the gas phase H-F covalent bond itself (0.92 Å),<sup>23</sup> the observed HF bond distance is substantially increased, ruling out any form of covalent interaction between H1 and F3. In comparison with reports of a hydrogen bonded fluoride-cryptate crystal structure, featuring six N-H…F interactions (N to F distance of *ca.* 2.8 Å),<sup>24</sup> the intramolecular N to F distance [2.996(4) Å] distance for **11b** does appear reasonable for hydrogen bonding to occur between H1 and F3. In addition, in the solid state at least, these hydrogen bonded units are linked *via* additional intermolecular H…F interactions (2.124 Å) into centrosymmetric dimers [an effect which clearly has an influence on the bond angles of the F(3)-H(1)-N(1) unit, 142.49(19)°]. From the crystal structure of **11b** therefore, it is clearly evident that the extent of HF bond rupture on binding is severe. Nevertheless, it is probably within reason to conclude that these parameters do constitute a weak hydrogen-bonding interaction, and that the complexation of hydrogen fluoride by compound **11a** occurs *via* discrete B-F<sup>-</sup>/N-H<sup>+</sup> interactions, rather than complete molecular binding, in which case a much smaller HF distance would be expected.

Finally, it should be noted that alternative convenient sources of HF include hydrogen fluoride-pyridine complex [( $C_5H_5N$ )·HF<sub>~2</sub>, 70% HF] and triethylamine trihydrofluoride (Et<sub>3</sub>N·3HF). Reaction of these reagents with compounds **9a**, **10a** and **11a**, yield identical products to those found from the analogous reaction with collidine-HF (*i.e.* **9b**, **10b** and **11b**), as judged by <sup>11</sup>B and <sup>19</sup>F NMR spectroscopy.

#### 5.3.3 Electrochemical HF detection by Lewis acid/Lewis base receptors

The process of fluoride recognition by ferrocene-based boryl Lewis acids has already been analysed by cyclic voltammetry (Chapter Four, this thesis). In light of these results, similar CV experiments were also exploited to follow the reaction of hydrogen fluoride with 9a, 10a and 11a. Figures 5.13, 5.14 and 5.15 depict the respective CV experiments for compounds 9a, 10a and 11a; in which the blue CV traces represent the free compounds, and the red CV trace the compounds formed on addition of HF. Table 5.5 lists a summary of derived parameters (with ferrocene as the reference compound).



Figure 5.13 Cyclic Voltammogram of 9a (blue trace) and 9b (red trace) in MeCN with [" $Bu_4N$ ]PF<sub>6</sub> as supporting electrolyte. Scan rate = 100 mV/s.







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Compound	Solvent	Peak-Peak separation (Ep <sup>ox</sup> -Ep <sup>red</sup> ) (mV)	E <sub>1/2</sub> Relative to FcH (E <sub>1/2</sub> Ref.) (mV) <sup>a</sup>
9a	MeCN	85	-190.5
9b	MeCN	75	-321
9a+HF	MeCN	85	-311.5
10a	MeCN	96	-0.5
10b	MeCN	80	-328.5
10a+HF	MeCN	75	-310
11a	MeCN	85	+37.5
11b	MeCN	75	-43
11a+HF	MeCN	85	-65.5

Table 5.5 Electrochemical data of Lewis acid/Lewis base compounds 9a, 10a, 11a and their HF reaction products 9b, 10b, 11b,  $["Bu_4N]PF_6$  as supporting electrolyte.

<sup>a</sup> FcH vs S.C.E:  $E_{1/2} = 0.46$  V (DCM), 0.40 V(MeCN)

The experiments summarised in the table above enable a direct comparison to be made between the isolated HF addition products **9b**, **10b** and **11b**, and the compounds formed in situ from collidine-HF treatment of **9a**, **10a**, **11a**. In this respect, the CV results indicate close agreement between the two sets of electrochemical data, *i.e.* common reaction products are observed. Of importance in understanding the electronic effects associated with the various ferrocene-based substituents are the electrochemical potentials relative to ferrocene itself. In all cases of HF treatment, it is evident that a shift to more negative potential occurs when each of the mixed Lewis acid/Lewis base receptors **9a**, **10a** and **11a** are reacted with  $\geq 3$  equivalents of hydrogen fluoride. For example, **9a** and **10a** on treatment with the HF

source produce an electrochemical response, such that the free compounds (black CV traces) shift to a common oxidation potential (represented by the red CV traces in Figures 5.13 and 5.14 respectively). This can be explained in terms of the formation of the common  $[FcBF_3]^-$  product, which is significantly easier to oxidise than ferrocene itself (*ca.* 300 mV), presumably due to its negative charge. This result is similar to the shift in oxidation potential observed on fluoride binding to the monoboryl species 2a and 3a (*ca.* -500 mV, Chapter Four). Relative to the free compounds 9a and 10a, however, the shift in oxidation potential on reaction with HF is larger for 10a than 9a, presumably due to the absence of a N-B donor/acceptor interaction in 10a. The intramolecular base-stabilised compound 9a is itself easier to oxidise compared with the non-base stabilised system 10a due to the difference in electron donating/withdrawing properties associated with three- and four-coordinate pendant boryl units.

The formation of 11b, from collidine-HF and 11a, is characterised by a smaller shift (black to red CV trace) in the oxidation potential, presumably because the HF reaction product is an overall *charge neutral* complex, in contrast to  $[FcBF_3]^-$  in 9b and 10b. The shift in oxidation potential from the neutral boronic acid 11a to the neutral HF-adduct 11b is still negative however (-80 mV), due to the transformation of the directly bonded net-electron accepting boryl moiety in 11a, to a net-electron donating  $-BF_3^-$  group as in 11b. Therefore, it can be concluded that *N*,*N*-dimethylaminomethylferrocene boronic acid, 11a, is an effective organometallic receptor for the electrochemical detection of hydrogen fluoride.

### 5.3.4 HCl/["Bu<sub>4</sub>N]F treatment of receptors 9a and 11a

Another way to examine HF binding by receptors such as 9a and 11a is by the sequential addition of H<sup>+</sup> and F<sup>-</sup>, thus employing a more stepwise approach to binding.

The process of hydrogen fluoride addition was therefore attempted via the sequential addition of HCl, followed by fluoride as  $[^{n}Bu_{4}N]F$  to a solution of the intramolecularly base-stabilised system 9a in acetonitrile solution. Upon addition of one equivalent of HCl as a 1.0 M solution in ether, the <sup>11</sup>B NMR indicates an upfield shift from  $\delta_B = 13$  to  $\delta_B = 30$ , as would be as expected from protonation of the Lewis basic amine, and therefore removal of the intramolecular N-B interaction to yield a three coordinate boron centre. The important observation to be made from the <sup>11</sup>B response to HCl treatment is that binding of chloride does not occur, since a chemical shift characteristic of four-coordinate boron (as in the starting material 9a) is not seen. Thus, protonation of the Lewis basic component is not accompanied by CI complexation upon HCl addition. Presumably therefore, the same applies for the other, less strongly coordinating halide anions (Br,  $\Gamma$ ), thus indicating the potential selectivity of the system for hydrogen fluoride against the other hydrogen halides. However, the <sup>1</sup>H NMR of the precipitate at this stage of the reaction reveals that H<sup>+</sup> coordination by Lewis basic nitrogen does occur, but is also accompanied by B-O bond cleavage leading to loss of the Lewis basic component and formation of ferroceneboronic acid.<sup>14,16</sup> Subsequent fluoride addition ( $\leq 1$  equivalent) in the form of ["Bu<sub>4</sub>N]F simply yields the fluoride adduct of ferroceneboronic acid as studied by Shinkai et. al.,<sup>15</sup> apparent in the <sup>11</sup>B NMR as a broad singlet at  $\delta_{\rm B}$  =12, while excessive additions of ["Bu<sub>4</sub>N]F serve to fluorinate the boron centre forming [FcBF<sub>3</sub>]<sup>-</sup>, evident as a distinct quartet in the <sup>11</sup>B and <sup>19</sup>F spectrum [ $\delta_B = 3.7$  ppm

(q,  $J_{B-F} = 49.8$  Hz),  $\delta_F = -136$  (q,  $J_{F-B} = 48.6$  Hz)]. As a consequence, HCl/[<sup>n</sup>Bu<sub>4</sub>N]F treatment of 10a was not attempted.

The analogous reaction with **11a** as indicated by <sup>11</sup>B NMR, on the other hand is thought to yield the protonated intermediate on the addition of one equivalent of dry HCl in ether, since no change in the chemical shift from the starting material **11a** is seen ( $\delta_B$  30 ppm). Subsequent addition of three equivalents of tetra-*n*butylammonium fluoride gives rise to identical <sup>11</sup>B and <sup>19</sup>F NMR spectra as for **11b**, in accordance with Scheme 5.4. Furthermore, the fact that upon addition of the acid, no change in <sup>11</sup>B NMR shift is seen, tends to suggest that protonation of the amine component is not accompanied by chloride binding and the system is hence selective solely for fluoride.



Scheme 5.4 HF-adduct formation via HCl/["Bu<sub>4</sub>N]F treatment of 11a.

The chemistry displayed by dimethylaminomethylferrocene boronic acid, **11a**, on treatment with HCl/[<sup>n</sup>Bu<sub>4</sub>N]F is also revealed by cyclic voltammetry, Figure 5.16. Relative to the ferrocene FcH/[FcH]<sup>+</sup> redox couple, oxidation of **11a** occurs at the usual potential (+37.5 mV, blue trace), but upon the addition of HCl (1.0M solution in ether), the reversible oxidation process is shifted by +149.5 mV to a more positive potential (red trace). This is consistent with the process of protonation since the

positive species so formed would be more difficult to oxidise. This shift to more positive potential supports the fact that protonation of Lewis basic nitrogen is *not* accompanied by chloride binding. If, in addition to H<sup>+</sup> complexation, Cl<sup>-</sup> binding was to take place, the resulting overall charge neutral species thus formed would be expected to possess an oxidation potential more comparable with 11b (-43 mV w.r.t. FcH/[FcH]<sup>+</sup>), and would certainly not be expected to occur at +187 mV, relative to ferrocene. This again reflects the selectivity of the system for fluoride over the other less strongly coordinating halide anions. The successive addition of ["Bu<sub>4</sub>N]F to the electrochemical experiment induces a further shift in oxidation potential of -224.5 mV (green trace, relative to that observed on addition of HCl alone). This oxidation potential is consistent with the presence of 11b, by comparison with an authentic sample. The overall shift in oxidation potential on H<sup>+</sup>/F<sup>-</sup> coordination is therefore -75 mV under these conditions, which is essentially identical to that witnessed in the analogous collidine HF reaction with 11a.





#### 5.4 Conclusions and suggestions for further research

The synthesis of the intramolecular base-stabilised system **9a** and the nonbase-stabilised system **10a** can be achieved in reasonable yields thereby generating mixed Lewis acid/base systems with similar functionalities to the literature compound **11a**. Spectroscopic and X-ray diffraction studies indicate distinct differences in their structure, although all three systems offer the potential for hydrogen fluoride sensing.

The binding experiments involving hydrogen fluoride yield a clear and concise explanation of the chemistry that takes place with 9a, 10a and 11a. Common features include cleavage of the B-O boronic ester linkage to produce a  $CpBF_3^-$  moiety; in the cases of 9a and 10a this leads to loss of the Lewis basic amine. However, when the Lewis acid and Lewis base functions are built onto the ferrocene backbone as separate carbon-bound functional groups (11a), loss of the necessary Lewis base for H<sup>+</sup> coordination does not occur, and effective HF binding is found to take place. The process has been successfully analysed spectroscopically, structurally and electrochemically, providing significant evidence of HF recognition. Alternative routes have also been explored yielding the same result.

Although compound **11a** has been shown to act as an electrochemical sensor for hydrogen fluoride, the ideal scenario of a colorimetric hydrogen fluoride sensor appears to be more of a challenge. The colorimetric fluoride ion sensor **2b** (Chapter Four)<sup>17</sup> functions by aerobic oxidation of the *bis*-fluoride adduct which possesses a double negative charge, so enabling oxidation by atmospheric  $O_2$ . The HF-receptor **11a**, on the other hand, binds HF to form a neutral species, characterised by a much smaller shift in oxidation potential, and as a consequence, is unlikely to undergo aerobic oxidation. It may therefore prove useful to synthesise ferrocene-based systems featuring two, three or even four HF receptor functions to aid oxidation and produce a colour change on binding. Alternatively, the inclusion of a more powerful oxidising agent within the system (compared to aerobic  $O_2$ ) may bring about the colourimetric response desired for molecular sensing.

Furthermore, it would be advantageous to synthesise derivatives of the boronic acid **11a**, in the form of cyclic boronic esters,<sup>6</sup> that would be potentially immune to B-O cleavage in the presence of HF, and hence give a resulting adduct featuring solely one HF molecule. However, given the strong hydrolytic properties of HF, boronic esters such as those synthesised in Chapter Three would probably be unsuitable, and presumably would result in loss of the ester moiety and formation of the parent diol on HF addition.

#### 5.5 References for Chapter Five

- (a) H. Sohn, S. Létant, M. J. Sailor, W. C. Trogler, J. Am. Chem. Soc., 2000, 122, 5399; (b) S. W. Zhang, T. W. Swager, J. Am. Chem. Soc., 2003, 125, 3420.
- 2. G. Marr, R. E. Moore, B. W. Rockett, J. Chem. Soc. (C), 1968, 24.
- 3. A. Ori, S. Shinkai, J. Chem. Soc., Chem. Commun., 1995, 1771.
- H. Yamamoto, A. Ori, K. Ueda, C. Dusemund, S. Shinkai, *Chem. Commun.*, 1996, 407.
- 5. J. C. Norrild, J. Chem. Soc., Perkin Trans. 2, 2001, 719.
- 6. J. C. Norrild, I. Søtofte, J. Chem. Soc., Perkin Trans. 2, 2001, 727.
- 7. J. C. Norrild, I. Søtofte, J. Chem. Soc., Perkin Trans. 2, 2002, 303.
- S. Arimori, S. Ushiroda, L. M. Peter, A. Toby, A. Jenkins, T. D. James, Chem. Commun., 2002, 2368.
- 9. V. Barba, R. Xochipa, R. Santillan, N. Farfán, Eur. J. Inorg. Chem., 2004, 118.
- 10. S. Aldridge, R. J. Calder, D. L. Coombs, C. Jones, J. W. Steed, S. Coles, M. B. Hursthouse, New J. Chem., 2002, 26, 677.
- 11. T. Renk, W. Ruf, W. Siebert, J. Organomet. Chem., 1976, 120, 1-25.
- 12. A. Appel, H. Nöth, M. Schmidt, Chem. Ber., 1995, 128, 621.
- 13. R. J. Calder, PhD Thesis, Investigation of some novel transition metal boryl complexes, 2002, Chapter Five, 141.
- 14. R. Epton, G. Marr, G. K. Rogers, J. Organomet. Chem., 1978, 150, 93.
- 15. C. Dusemund, K. R. A. Samankumara Sandanayake, S. Shinkai, J. Chem. Soc., Chem. Commun., 1995, 333.
- 16. B. Floris, G. Illuminati, J. Organomet. Chem., 1978, 150, 101.
- 17. S. Aldridge, C. Bresner, I. A. Fallis, S. J. Coles, M. B. Hursthouse, Chem. Commun., 2002, 740.

18. Chapter 4, this thesis.

- 19. F. Jäkle, K. Polburn, M. Wagner, Chem. Ber., 1996, 129, 603.
- 20. T. D Quach, R. A. Batey, A. J. Lough, Acta Crystallogr. Sect. E, 2001, 57, m320.
- 21. S. Yamaguchi, S. Akiyama, K. Tamao, J. Am. Chem. Soc., 2001, 123, 11372.
- 22. H. E. Katz, J. Am. Chem. Soc., 1986, 108, 7640.
- 23. A. G. Sharpe, Inorganic Chemistry, 3rd edn, pp 408.
- 24. B. Dietrich, J. M. Lehn, J. Guilhem, C. Pascard, *Tetrahedron Lett.*, 1989, **30**, 31, 4125.

# Appendix One

## List of Publications

Multidentate Lewis acids: synthesis, structure and mode of action of a redox-based fluoride ion sensor. S. Aldridge, C. Bresner, I. A. Fallis, S. J. Coles, M. B. Hursthouse, Chem. Commun., 2002, 740.

The coordination chemistry of boryl and borate substituted cyclopentadienyl ligands. S. Aldridge, C. Bresner, Coordination Chemistry Reviews, 2003, **244**, 71-92.

Hydrogen-bonding motifs in the solid-state structure of ferroceneboronic acid. C. Bresner et al., Acta Cryst., 2004, E60, 1.

Selective Electrochemical Detection of Hydrogen Fluoride by Ambiphilic Ferrocene Derivatives. C. Bresner, S. Aldridge, I. A. Fallis, C. Jones, L. Ooi, Angew. Chem. Int. Ed., 2005, 44, 3606.

