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Relationships between basicity, redox behaviour of ferrocenylamines and their reactivity with Pt[II] compounds

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Abstract

pK_b values for the ferrocenylamines, [(η-$C_5H_4(CH_2)_xNH_2$)FeCp] $x = 1$, **2**, **3**; [(η-$C_5H_4CH_2NHR$)FeCp] R = Me, **4**, Ph, **5**; {[η-$C_5H_4CHR'NR_2$]FeCp} R′/R = H/Me, **6**, R′/R = H/Ph, **7**, Me/Me, **8**;[{η-$C_5H_4CHRNMe_2$)$_2$Fe] R = H **9**, Me **10**; [{1,2η-$C_5H_3(CH_2NMe_2)(PPh_2)$}FeCp] **11**, {1,2η-C_5H_3[CH(Me)NMe_2]$(PR_2$}}Fe[η-$C_5H_4(PPh_2)_n$] $n = 0$, R = ^{i}Pr **12**, Ph **13**, $n = 1$, R = Me **14**, are correlated with inductive, neighbouring group and steric effects. Corresponding salts have been synthesised. The pK_b has a marked influence on their chemistry. Protonation competes with complexation but *cis*-$PtCl_2L_2$ L = **1**–**3**, **5**, **7**, and *cis*-Pt(N–N)Cl_2 L = **8**, **9**, have been characterised. Two reversible couples [Fc^+A/FcA], [Fc^+AH^+/$FcAH^+$] (A = amine function) and an irreversible oxidation/protonation of A are linked by a EECE mechanism, but potentials for the first two are independent of the amine and similar to ferrocene. Nucleophilic attack by ferrocenylamines at the nitrile, protonation and ligand substitution are all observed with *cis*-[$PtCl_2(NCR)_2$]. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Ferrocenylamines; Platinum compounds; Basicity studies; Redox studies

1. Introduction

An assessment of the electronic effects of the ferrocenyl moiety on the acidity and basicity of functional groups has been the subject of many studies [1]. A recent determination [2] of pK_b values for [(η-$C_5H_4NH_2$)FeCp], [η-(m-$C_6H_4NH_2$)C_5H_4]FeCp and [η-(p-$C_6H_4NH_2$)C_5H_4] FeCp of 8.81, 9.66 and 9.85 respectively, indicated that these ferrocenylamines were weak Bronsted bases. However, it became clear to us from our work on biologically active ferrocenylamine derivatives that many with *N*-alkyl substituents behaved as stronger bases. Ferrocene compounds with nitrogen functionality have shown antiproliferative properties against a variety of carcinomas and tumours [3,4] but we found [5] that the toxicology of ferrocenylamines is strongly dependent on their basicity. This encouraged us to determine the pK_b for a range of ferrocenylamines and investigate whether this parameter can be correlated with other features of their chemistry. Ferrocenium salts are potential radiation sensitisers [6] and consequently it is important to know if the redox activity in the hypoxic cell could be predicted from the pK_b; this is explored in this paper. Recently, we reported [7–9] a series of cycloplatinated ferrocenylamine complexes with promising cytotoxicity but, like Neuse and co-workers [10], we found [11] that the propensity to protonation posed difficulties in the synthesis of cisplatin analogues with ferrocenylamine ligands. In this paper, we describe the competition between protonation and successful complex formation. Nucleophilic attack by amines on a benzonitrile ligand activated by coordination to Pt[II] to give amidines and amidates is well-documented [12]; the involvement of ferrocenylamines in this type of reaction provides a final illustration of the relationship between basicity and reactivity.

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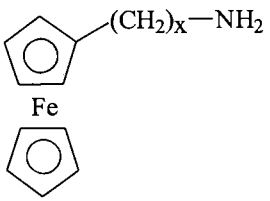
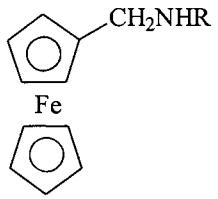
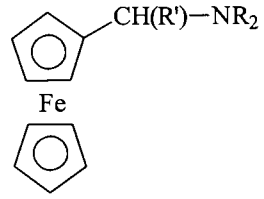


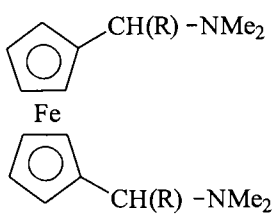
x = 0 **1**
1 **2**
3 **3**



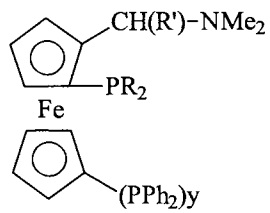
R = Me **4**
Ph **5**



R' = H R = Me **6**
R' = H R = Ph **7**
R' = Me R = Me **8**



R = H **9**
R = Me **10**



y = 0 R = Ph R' = H **11**
R = Ph R' = Me **12**
R = iPr R' = Me **13**
y = 1 R = Ph R' = Me **14**

2. Results and discussion

2.1. Basicity of ferrocenylamines

Titration of partially neutralised aqueous acidic solutions provided comparative pK_b data for the ferrocenylamines **1**–**14**, a series which provided diverse electronic and/or steric requirements. The pK_b values decrease in order: **5** > **7** > **1** > **14** > **12** > **13** > **9** ~ **11** > **6** ~ **2** > **3** > **10** > **4** > **8** (Table). The value for **1** is in good agreement with that determined by a different method [2] (Table 1).

Three factors may influence the trend in pK_b. First, the ferrocenyl group is inductively a net electron donor [1]. Second, when the non-protonated amine is directly bound to the cyclopentadienyl ring it is resonance-stabilised by delocalisation of the nitrogen lone pair [13]. Third, tertiary amines should have larger pK_b values than primary and secondary amines because of increased steric hindrance and reduced solvent stabilization of the cation [14]. These three factors would then impact to varying degrees on the relative thermodynamic stabilization of the free and quaternized amine. $FcNH_3^+$ is not resonance-stabilized but the free base is, with the result that the basicity of **1** is two to three orders of magnitude less than the other ferrocenylamines, except **5** and **7**. The inductive effect of the ferrocenyl substituent results in a lower pK_b for **1** compared to the organic analogue, $PhNH_2$ (pK_b = 9.39). In general, the *N*-methyl ferrocenylamines (**2**–**4**, **6**, **8**–**10**) have lower basicity than their organic analogues [14]. Interpolation of a saturated carbon group between the amine function and the ferrocene ring removes the neighbouring-group effect and the pK_b order is a function of the inductive capability of the

Table 1
pK_b and $E_{1/2}$ data for ferrocenylamines

Compound	Substituents on Cp ring		pK_b	$E_{1/2}^{a,b}$
1	NH_2	–	8.24	–
2	CH_2NH_2	–	5.12	0.47
3	$CH_2CH_2NH_2$	–	4.95	0.49
4	$CH_2NH(Me)$	–	4.65	0.48
5	$CH_2NH(Ph)$	–	9.73	0.48
6	CH_2NMe_2	–	5.17	0.48
7	CH_2NPh_2	–	9.54	0.49
8	$CH(Me)NMe_2$	–	4.30	0.47
9	CH_2NMe_2	1′-CH_2NMe_2	5.53	0.47
10	$CH(Me)NMe_2$	1-$CH(Me)NMe_2$	4.72	0.46
11	CH_2NMe_2	2-PPh_2	5.50	0.57
12	$CH(Me)NMe_2$	2-PPh_2	6.38	0.58
13	$CH(Me)NMe_2$	2-P^iPr_2	5.62	–
14	$CH(Me)NMe_2$	2-PPh_2 1′-PPh_2	6.73	0.64

[a] Couple **A**: reference decamethylferrocene; potential for ferrocene under the same conditions, 0.48 V.
[b] In acetone; square wave data at 20°C on Pt.

nitrogen and α-C- substituents, and steric effects. Thus, the inductive effect of the ferrocenyl group is negated and **5** and **7** have a pK_b slightly higher than their aniline counterparts. The introduction of one *N*-methyl substituent increases the basicity (**2**→**4**) but there is a decrease with a second (**6**) due to decreased stabilisation of the sterically hindered cation **6H**$^+$. Although this trend is identical to that in alkyl amines it is accentuated in the ferrocenylamines; compare the pK_b $MeNH_2$ (3.36), MeNHMe (3.29), $MeNMe_2$ (4.28). It is interesting that the compounds with an NMe_2 on each ring (**9**, **10**), are less basic than their counterparts with one (**6**, **8**) and the introduction of a C-methyl leads to the most basic ferrocenylamine (**8**). This is analogous to the trends in pK_b for arylamines. The addition of an *ortho* PR_2 substituent markedly reduces the basicity. This is particularly obvious for the $CH(Me)NMe_2$ derivatives where there is two orders of magnitude reduction on the introduction of one PPh_2 group (**12**) and a further 10-fold decrease with a PPh_2 in the other Cp ring (**14**). The fact that the pK_b is also dependent on the nature of the phosphorus substituent (cf **12** and **13**) could be interpreted as suggesting that the trend with PR_2 substitution is an inductive effect. However, PR_2 is not an electron-withdrawing group and the evidence above suggests that inductive effects are not transmitted to the N terminus, so the decreased basicity is most likely due to destabilisation of the cation. Steric effects would seem to be a significant factor in determining the basicity of ferrocenylamines.

Orange salts (with either Cl^- or $PtCl_4$ as counterion) were characterised in order to confirm the site of protonation, investigate possible steric effects and to study the effect of protonation on the redox properties. Typically, protonation of the amine function is manifested by a broad ν(N–H) band around 2600 cm^{-1} and a shift downfield of all ^1H and ^{13}C resonances compared to the free ligand-these are very useful diagnostic tools. In our experience, many samples of purported complexes of ferrocenylamines with metal ions have these features in 'pure' samples, an important observation as biological activity can be masked by protonated impurities. The downfield NMR shift on protonation is not as large as that occurring on complexation to a metal ion. Consequently, the position of the NMe_2 resonance for **6**, for example, is diagnostic of the free ligand ($\delta = 2.1$–2.2), protonation ($\delta = 2.4$–2.7) and complexation ($\delta = 2.8$–3.2).

2.2. Redox properties

An intriguing observation was made during our studies on Pt[II]-complexation and protonation of ferrocenylamines p$K_b < 5$ that many products appeared from NMR results to be contaminated by traces of paramagnetic ferrocenium salts; this has also been noted with biferrocenylamines [15,16]. We therefore carried out an electrochemical study of both the ferrocenylamines and their Pt[II] complexes (vide infra) to see if the basicity impinged on the redox properties.

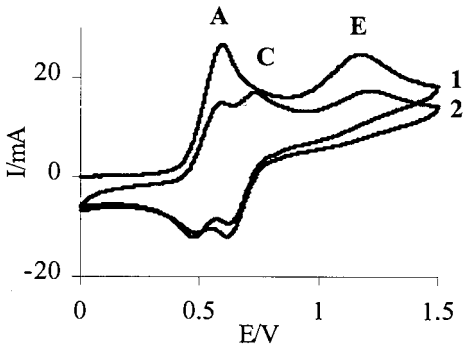


Fig. 1. Cyclic voltammogram of **6** in acetone: Pt, 20°C, TMEAP 0.1 M, scan rate 400 mV s^{-1}.

Ferrocenylamines **2**–**14** show a single chemically and electrochemically reversible, one-electron, couple **A** in their cyclic voltammograms or square wave plots when the initiating sweep range is from 0.0 V out to $E_{1/2}$ + 0.3 V (Figs. 1–3) due to the characteristic oxidation of the ferrocene redox centre. $E_{1/2}$ values for **A** (Table) were independent of the solvent. What was unexpected was that all non-protonated ferrocenylamines without PR_2 groups were oxidised at approximately the same potential as ferrocene; normally, $E^{+/0}$ [Fc] is very sensitive to the substituent on the Cp ring [17]. Furthermore, the potential was not influenced by the stereochemistry as $E_{1/2}$ [***R*-10** = ***S*-10**]. The ground states for the ferrocenium ion ($^2E_{2g}$) and ferrocene both have the electron density largely on the iron [18] and their energy may not vary greatly once a CH_2 isolates the amine function from the Cp ring. Nevertheless, it is surprising that difference in solvation energies between the neutral and oxidised species do not have a greater impact on the thermodynamic parameters. It was anticipated that **1** would be the most easily oxidised but strong adsorption

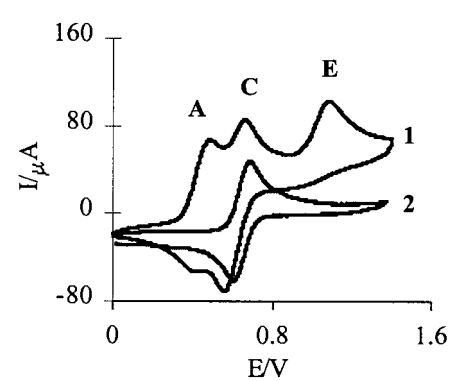


Fig. 2. Scan 1: cyclic voltammogram of **8** in CH_2Cl_2; Pt, 20°C, $TBAPF_6$ 0.1 M, scan rate 200 mV s^{-1}. Scan 2: **8H**$^+$ under the same conditions.

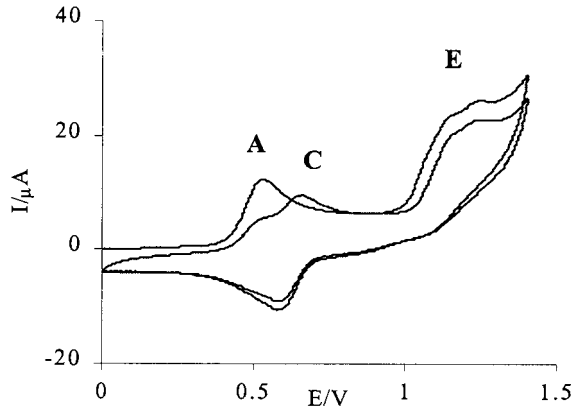


Fig. 3. Cyclic voltammogram of **7** in CH_2Cl_2: Pt, 20°C, $TBAPF_6$ 0.1 M, scan rate 200 mV s^{-1}.

on the electrode gave non-reproducible results. A PPh_2 substituent has a marked effect on $E_{1/2}$ especially for those derived from **8** (**12**–**14**) with the ferrocenyl redox centre becoming more difficult to oxidise; this PPh_2 substituent effect is cumulative (cf **12** and **14**). This trend could be ascribed to the π-acceptor properties of the phosphine (this is in contrast to the pK_b trend, vide supra) but could equally be due to decreased solvation of the cation and steric hindrance associated with electron transfer at the electrode surface.

When the potential range is extended beyond 1.1 V an additional irreversible wave **E** is observed on the first anodic scan with at least a one-electron transfer and approximately 1.0 V positive of **A** (Figs. 1–3). Anodic oxidations of aliphatic amines typically involve the formation of the amine or ammonium salt which arise from hydrogen abstraction from the solvent by the generated cation radical whereas radical coupling is favoured by aromatic amines [19]. A similar process can be assigned to **E** for **2**–**4**, **6**, **8**–**10** and its potential is only dependent on the N-substituent.

$$[(\eta\text{-}C_5H_4CH_2NRR')Fe^+Cp] \overset{-e\,(E)}{\leftrightarrow} [(\eta\text{-}C_5H_4CH_2N^{+\bullet}RR')Fe^+Cp] \overset{solv\,(H)}{\leftrightarrow} [(\eta\text{-}C_5H_4CH_2NH^+RR')Fe^+Cp] \quad (1)$$

This assignment was confirmed by the isolation of $\mathbf{8H^{2+}}$ from the bulk electrolysis of **8**. An additional cathodic wave $\mathbf{C_c}$ appears on the reverse sweep with the anodic component $\mathbf{C_a}$ on subsequent scans. Couple **C**, approximately 0.2 V positive of **A** is assigned to a reversible one-electron couple involving oxidation of the protonated ferrocenylamine to the ferrocenium species; this is the only couple seen in the solution electrochemistry of the salts (Fig. 2). In the potential range 0.00–1.7 V the relative currents of the couples **A** and **C** are determined by the scan rate but are essentially independent of the solvent and basicity of the ferrocenylamine. $\mathbf{C_c}$ dominates on the reverse scan at fast scan rates ($\gg$ 200 mV s^{-1}) because of the higher concentration of the protonated species at the electrode surface. The shift in potential $\mathbf{A} \rightarrow \mathbf{C}$ is simply a consequence of the higher coulombic charge on the salt and consequently there is a linear correlation between the electrostatic charge and the difference in potential; that is, the number of NMe_2 groups per redox centre (cf **6** with **9**, **8** with **10**). $E^{+/0}$ for **5** has two components on the anodic scan but only $\mathbf{C_c}$ and not $\mathbf{A_c}$ on the reverse scan at scan rates $>$ 200 mV s^{-1} (Fig. 3). Thus, protonation rather than radical coupling dominates. In contrast, multiple cathodic processes are seen in voltammograms for **7,** including a species reduced at 0.1 V, which may arise from radical coupling involving the N–Ph group. Additional processes close to 1.5 V are seen in the phosphine derivatives, **12**–**14**, associated with oxidation of the PPh_2 group and at potentials comparable to dppf [20], which obscure **E** for these compounds.

$$[(\eta - C_5H_4CH_2NRR')FeCp] \overset{A}{\leftrightarrow} [(\eta - C_5H_4CH_2NRR')Fe^+Cp] \overset{E}{\Rightarrow} [(\eta - C_5H_4CH_2HN^+RR')Fe^+Cp] \overset{C}{\rightarrow} [(\eta - C_5H_4CH_2HN^+RR')Fe^+Cp] \quad (2)$$

In summary, the electrochemistry of ferrocenylamines arises from an EECE mechanism involving both the protonated and non-protonated forms (Eq 2). Controlled potential electrolysis of a ferrocenylamines at **E** offers a route to new ferrocene derivatives; this is currently being explored.

2.3. Ferrocenylamine-platinum(II) complexes

Syntheses of *cis*-PtL_2Cl_2, from K_2PtCl_4, or the labile precursors $Pt(COD)Cl_2$ and *cis*-$Pt(dmso)_2Cl_2$, were unsuccessful when L = **4, 6, 7**. In-situ monitoring of reaction progress by ^{195}Pt-NMR suggested that small amounts of a *cis*-PtL_2Cl_2 complex were formed in the initial stages of the reaction but protonation of the amine ligand effectively competed with complexation, even in the presence of K_2CO_3. In contrast, good yields of *cis*-$[PtL_2Cl_2]$ L = **1–3, 5**, *cis*-$[PtLCl_2]$ L = **9, 10**, and the reported [21] *cis*-$[Pt(\mathbf{11})Cl_2]$ and *cis*-$[Pt(\mathbf{14})Cl_2]$, were obtained by stirring a mixture of K_2PtCl_4 and the appropriate ligand in CH_2Cl_2/H_2O at r.t. Two related compounds, $Pt[Fc–CH(Me)NH_2]_2Cl_2$, $Pt[FcCH_2NH_2–CH_2]_2Cl_2$ have been prepared [10] from K_2PtCl_4 in ethanol.

The dichotomy in behaviour, protonation versus complexation, correlates with the ligand pK_b values. Primary amines and *N*-aryl secondary amines readily coordinate to Pt[II]. With the, the most basic ferrocenylamine ligands-secondary **4** and tertiary-*N*-methyl **8-** the particular thermodynamic stability of the protonated species leads to preferential salt formation. Despite the decreased basicity of **6** the poor nucleophilicity of tertiary amines

towards complexation drives the equilibrium towards protonation. The additional thermodynamic stabilization resulting from chelate formation provides the necessary impetus for complexation to dominate with the other tertiary amines **9–14**. Work with other *N*-alkyl ferrocenylamines substantiates these conclusions [22]. With **7**, the initially formed *cis*-[PtL_2Cl_2] rapidly decomposed and neither the protonated nor complexed product was isolated.

All of the Pt[II] complexes were yellow-crystalline solids, insoluble in water, but soluble in common organic solvents. The complex with **5** as ligand was usually isolated as a purple compound reminiscent of the so called 'platinum blues' due to the incorporation of a dye which is often a decomposition product of **5** without the intervention of Pt[II]. Two ν(Pt–Cl) bands are observed for the complexes of **1**, **3**, **5**, **11** which confirms a *cis*-configuration but one ν(Pt–Cl) band for **2** and the chelating ligands **13**, **14.** This is not unusual; for example, *cis*-$Pt(NH_3)_2Cl_2$ [23] and the red form of $Pt(bipy)Cl_2$ [24] have a single Pt–Cl band The ^{1}H-NMR spectra of the compounds with a N,N donor set often displayed paramagnetic broadening of the resonances, but the observed ^{195}Pt-NMR were consistent with the proposed donor set [25]. Cyclic voltammetry of the Pt[II] complexes showed that the potential of their reversible couples equivalent to **A** were ≈ 0.2 V *less* than the free ligand, a result which could be interpreted as a decrease in electron density on the ferrocenyl moiety on complexation, but more likely to be stabilisation of the charged ferrocenium species. If there is uncomplexed oxidised ferrocenylamine in a reaction solution it will oxidise the Pt[II] complex, which could account for the paramagnetic impurities noted in many samples of the complexes, but it is not clear what initiates the oxidation.

2.4. Reaction of ferrocenylamines with $(PhCN)_2PtCl_2$

A ^{1}H-NMR time-lapse study of the reaction of *cis*-$(PhCN)_2PtCl_2$ with **6** in d_6-benzene showed a singlet NMe_2 peak at 2.57 ppm at $T = 0$ which indicated immediate protonation. A broad resonance due to coordinated NMe_2 at 2.8–3.2 ppm grew in intensity and a concurrent time-lapse ^{195}Pt-NMR study showed that after 7 h the only Pt[II] product was one with a *cis*-2N coordination environment (δ 2170) consistent with a formulation *cis*-[(**6**)(PhCN)$PtCl_2$]. Similar results were obtained with *cis*-$(MeCN)_2PtCl_2$. Analytically pure samples of *cis*-[(**6**)(CN)$PtCl_2$] were not obtained because the salts were difficult to remove. Reaction of *cis*-$(PhCN)_2PtCl_2$ with the least basic secondary amine **5** gave yellow crystalline solids as the major products and an orange insoluble powder. Time-lapse ^{195}Pt-NMR showed the formation of two solution products and the chemical shifts, 2164 and 2248 ppm, were consistent with a *cis*-2N donor set. The ^{1}H- and ^{13}C-NMR indicated a set of two C_6H_5, one η-$C_{10}H_9$, CH_2 group and at least two CN functions. The relative intensities of ν(C≡N) (2275 cm^{-1}) and ν(C=N) (1711 cm^{-1}) (no ν(N–H) of $\mathbf{5H}^+$ were observed) and ν(Pt–Cl) modes in the infrared spectra depended on the preparation. Despite the variable spectroscopic data the analytical data were similar for each preparation and consistent with either [(**5**)(PhCN)$PtCl_2$] **15a** in which **5** has simply substituted one nitrile ligand, or a four-membered chelated amidine {[PhC($NPhCH_2Fc$)NH]$PtCl_2$}**15b** resulting from nucleophilic attack on the coordinated nitrile; we suggest that the yellow solids are mixtures of **15a** and **15b**.

3. Conclusion

Ferrocenylamines display a wide range of basicity, but not redox potential, which impacts significantly on their chemistry. Potential data for any ferrocenylamine needs to be carefully examined to ensure that protonation has not taken place prior to the i/V scan as this will occur in the double layer before it is obvious in the bulk solution. The propensity for *N*-alkyl ferrocenylamines to protonate and oxidise to the ferrocenium analogues needs to be considered when evaluating their biological activity. Interestingly, it is the *N*-aryl ferrocenylamines which show the most biological activity [5] suggesting that protonation of the more basic *N*-alkyl ferrocenylamines may be inhibiting their in vivo activity. Ferrocenylamines and their Pt[II] complexes undergo partial oxidation of the ferrocenyl redox centre in solution, by a mechanism which is not understood, which makes an NMR study of their interaction with DNA and proteins difficult. Furthermore, recent cell culture work has shown that oxidised water-soluble ferrocenylamines are not active against hypoxic cell lines [26]. Future work will concentrate on sugar ferrocenylamines which can be targeted to specific cell functions.

4. Experimental

Most of the ferrocenylamine compounds have acrid odours, therefore all synthetic work was performed in a fumehood. All reactions were carried out under an atmosphere of dry nitrogen. Solvents were purified and dried by standard methods and the ferrocenylamines and Pt[II] precursors prepared by literature methods: **1-14** [27–31], *cis*-$Pt(DMSO)_2Cl_2$ [32], $Pt(COD)Cl_2$ [33], and $Pt(PhCN)_2Cl_2$ [12]. NMR, IR and UV–vis spectra were recorded on a Varian 300 MHz VXR or 200 MHz Gemini, Digilab FTIR and Perkin Elmer Lambda 9 spectrometers respectively. ^{195}Pt-NMR were referenced

to Na_2PtCl_6. Microanalyses were carried out by the Campbell Microanalytical Laboratory, University of Otago Electrochemical measurements were performed with a three-electrode cell using an EG & G PAR 273a at scan rates 0.05–10 V s^{-1}. A polished Pt electrode was used; all potentials are referenced against decamethylferrocene uncorrected for junction potentials, the supporting electrolyte (TEAP) 0.1 M and the substrate ca. 1×10^{-3} M.

4.1. Determination of K_b value of ferrocenyl ligands

A mixture of 0.1 M NaCl (5 cm^3) in water and acetone (8 cm^3) was added to a cell equipped with a pH electrode and stirrer and the required amount of ferrocenylamine was then added to give a substrate concentration of 0.01 mol dm^{-3}. An inert atmosphere was maintained in the cell for the duration of the experiment. The mixture was titrated with freshly prepared 0.01 M HCl solution with steps of 0.1 cm^3 between each addition and the pH was recorded after each addition. All measurements were obtained at 20°C and the solstat EPM-900 pH meter was calibrated using appropriate buffer solutions.

4.2. Salts of ferrocenylamines

Hydrochloride salts of the ferrocenylamines were precipitated by bubbling HCl gas through an ether solution of the appropriate ligand; to prepare $PtCl_4^{2-}$ salts K_2PtCl_4 was dissolved in a small quantity of water and added to above solutions. **$(3H^+)_2 \cdot PtCl_4^{2-}$-.** M.p. 222–224°C with dec. Calcd. for $C_{24}Cl_4Fe_2H_{32}N_2Pt$: C, 36.16; H, 4.04; N, 3.51; Cl, 17.79%. Found: C, 36.06; H, 4.10; N, 3.80; Cl, 16.55%. ^{1}H-NMR (dmso): 2.60(2H, C$\underline{H}_2$$CH_2N$), 3.00(2H, CH_2C$\underline{H}_2$$CH_2N$), 4.11($\eta$-$C_5H_4$), 4.16($\eta$-$C_5H_4$). IR (KBr, cm^{-1}): 2854, 2958 $\nu(NH_3^+)$. Λ_m, (dmso): 104. UV–vis (λ_{max}, nm, dmso): 419 ($\varepsilon = 229$). **$(4H^+)_2 \cdot PtCl_4^{2-}$**. M.p. 186°C(dec). Calcd. for $C_{24}Cl_4Fe_2H_{33}N_2Pt$: C, 36.16; H, 4.05; N, 3.51%. Found: C, 36.38; H, 4.04; N, 3.93%. ^{1}H-NMR (dmso): 3.32 (3H, NCH_3), 3.92 (2H, CH_2N), 4.22 (η-C_5H_5), 4.26, 4.39 (η-C_5H_4), L_m (dmso): 100. UV–vis (λ_{max}, nm, dmso): 426 (258). **$(5H^+)_2 \cdot PtCl_4^{2-}$** $C_{34}H_{36}Cl_4$ Fe_2N_2Pt requires: C, 44.52; H, 3.52; N, 3.05. Found: C, 44.63; H, 3.67; N, 3.14. M.p. 183°C dec. ^{1}H-NMR (dmso): 3.74 (2H, CH_2N), 4.08–4.60 (9H, η-C_5H_5, η-C_5H_4), 7.20–7.40 (m, C_6H_5). **$6H^+ \cdot Cl^-$** m.p.: 158–160°C. Calcd. for $C_{13}FeH_{18}NCl$: C, 55.85; H, 6.49; N, 5.01%. Found: C, 55.68; H, 6.47; N, 4.95%. IR (KBr, cm^{-1}) 2368–2646 (s, br) ν(N–H). ^{1}H-NMR (δ, $CDCl_3$): 2.64 (s, 6H, NC$\underline{H}_3$); 4.09 (s, 2H, C$\underline{H}_2$N); 4.20 (s, 5H, η-$C_5\underline{H}_5$Fe); 4.32 and 4.40 (η-$C_5\underline{H}_4$Fe). **$7H^+ \cdot Cl^-$** m.p. 208°C. Calcd. for $C_{14}FeH_{19}N.HCl$: C, 57.27; H, 6.87; N, 4.77%. Found: C, 57.20; H, 6.84; N, 4.73%. ^{1}H-NMR (d, $CDCl_3$): 1.89 (bs, 3H, CHC$\underline{H}_3$); 2.48 and 2.58 (2 x s, 6H, NC$\underline{H}_3$); 4.20 (s, 5H, η-$C_5\underline{H}_5$Fe); 4.28, 4.34 (η-$C_5\underline{H}_4$Fe); 4.46 (bs, 1H, C$\underline{H}$$CH_3$). **$9H^+ \cdot Cl^-$** mp. 200°C. $C_{19}H_{30}ClFeNP$ requires: C, 64.74; H, 5.87; N, 3.02. Found: C, 64.68; H, 5.82; N, 2.85. ^{1}H-NMR: 2.34 (3H, NCH_3), 2.62 (3H, NCH_3), 3.98 (h-C_5H_5), 4.23, 4.65, 5.30 (h-C_5H_5), 7.31–7.65 (10H, C_6H_5), 4.30–4.55 (CH_2N). **$10H^+ \cdot Cl^-$** $C_{38}H_{37}ClFeNP_2$ requires: C, 68.94; H, 5.64; N, 2.11. Found: C, 69.05; H, 6.02; N, 2.21. ^{1}H-NMR: 1.85 (3H, C$\underline{H}_3$CH, $J = 6.99$ Hz), 2.18 (3H, NCH_3), 2.21 (3H, NCH_3), 3.49–4.58 (8H, η-C_5H_5), η-C_5H_3; C$\underline{H}$$CH_3$), 6.87–7.66 (20H, Ph).

4.3. Preparations of cis-$Pt(L_2)Cl_2$ and cis-Pt(P-N)Cl_2

Reactions of K_2PtCl_4 (1 mmol) in water (1 cm^3) with the ligands L (1 or 2 mmol as appropriate) in CH_2Cl_2 (10 cm^3) were carried out with vigorous stirring. The red colour of $PtCl_4^{2-}$ gradually fades from the aqueous layer as reaction proceeds and when the aqueous phases became clear (3–20 h) the organic phases were separated and filtered. Some products precipitated while others were soluble in CH_2Cl_2. The precipitates were washed with CH_2Cl_2 and dried in vacuo to give product. For the isolation of CH_2Cl_2 soluble products, hexane was added to the filtrates at 0°C. **L = 1** Yield, 49%. M.p. 178–180°C. Calcd. for $C_{20}Cl_2Fe_2H_{22}N_2Pt$: C, 35.96; H, 3.32; N, 4.19%. Found: C, 35.59; H, 3.62; N, 3.95%. IR (KBr, cm^{-1}): 3444 ν(N–H); 1628 $\nu d_{(N-H)}$. (nujol) 324, 309 ν(Pt-Cl). ^{1}H-NMR (δ, d^6-dmso): 3.32 (m, η^5-$C_5\underline{H}_4$Fe); 3.37 (s, η^5-$C_5\underline{H}_5$Fe); 4.20–4.40 (bs, 2H, NH_2). UV–vis (dmso, λ_{max}): 448 ($\varepsilon = 979$). **L = 2** Yield, 32%. M.p. 250–252°C. Anal. Calcd. for $C_{22}Cl_2Fe_2H_{26}N_2Pt$: C, 37.96; H, 3.76; N, 4.02; Cl, 10.19%. Found: C, 37.55; H, 3.63; N, 3.82; Cl, 9.89%. IR (KBr, cm^{-1}): 3267 $\nu_{(N-H)}$; 1577 $\nu_{(N-H)}$ (nujol): 324 $\nu_{(Pt-Cl)}$. ^{1}H-NMR (d, $CDCl_3$): 3.33 (bs, 2H, C$\underline{H}_2$N); 4.10 (s, 7H, η^5-$C_5\underline{H}_5$); 4.29 (m, 2H, η^5-$C_5\underline{H}_5$); 4.90 (bs, 2H, N$\underline{H}_2$). UV–vis (dmso, λ_{max}): 428 (295). **L = 3** Yield, 46%. M.p. 220–222°C. Calcd. for $C_{24}Cl_2Fe_2H_{30}N_2Pt$: C, 39.80; H, 4.17; N, 3.86; Cl, 9.79%. Found: C, 38.96; H, 4.17; N, 3.80; Cl, 9.70%. UV–vis (CH_2Cl_2, nm): 422 (658). **L = 5** Yield, 15%. M.p. 148–150°C. Calcd. for $C_{34}Cl_2Fe_2H_{34}N_2Pt$: C, 48.14; H, 4.04; N, 3.30; Cl, 8.36%. Found: C, 47.97; H, 3.97; N, 3.20; Cl, 10.83, 10.68, 11.01%. IR (KBr, cm^{-1}): 3194 (b) $\nu_{(N-H)}$ (nujol): 334, 328 ν(Pt–Cl). UV–vis (CH_2Cl_2, nm): 345 (3455); 522 (1244). **L = 11** Yield, 62%. M.p. 220°C. Calcd. for $C_{16}Cl_2FeH_{24}N_2Pt.2H_2O$: C, 31.91; H, 4.60; N, 4.65; Cl, 11.77%. Found: C, 31.74; H, 4.55; N, 4.09; Cl, 11.77%. IR (cm^{-1}) 326 ν(Pt–Cl). UV–vis (CH_2Cl_2, nm): 413 (493). **L = 9** Yield, 45%. M.p. 230–232°C. Calcd. for $C_{25}Cl_2FeH_{26}NPPt$: C, 43.31; H, 3.78; N, 2.02; P, 4.47%. Found: C, 43.46; H, 3.95; N, 1.91; P, 4.58%. IR (cm^{-1}): 313, 302 ν(Pt–Cl). ^{1}H-NMR ($CDCl_3$): 2.79 and 3.43 (2 × bs, 3H, NC$\underline{H}_3$); 3.70–4.60 (m, 10H, η^5-$C_5\underline{H}_3$, C$\underline{H}_2$N); 6.85–8.40 (m, 10H, P($C_6\underline{H}_5$)$_2$). ^{31}P-NMR ($CDCl_3$): −7.35 ($J_{Pt-P} = 3941$ Hz). UV–vis (CH_2Cl_2, λ nm): 461 (535).

4.4. Reaction of $Pt(PhCN)_2Cl_2$ with **5** and **6**

$Pt(PhCN)_2Cl_2$ (0.5 g, 1.08 mol) was stirred with **5** (0.63 g, 2.16 mmol) in 75 cm^3 of methanol for 3 days at r.t. The solvent was evaporated (water bath at r.t.) and a yellow solid **13** appeared on addition of CH_2Cl_2, to the resulting brown syrup. Further solid precipitation occurred on cooling to 4°C. The mixture was centrifuged, the yellow brown pallet washed and centrifuged in benzene three times to remove starting material, washed once with hexane and dried in vacuo. Found: C, 43.00; H, 3.51; Cl, 11.00; N, 4.00%. $C_{24}H_{22}Cl_2FeN_2Pt$ requires C, 43.65; H, 3.36; Cl, 10.74; N, 4.24. IR (cm^{-1}): 2271 (νC≡N): 1732 (νC=N); 1651 (Ph of **5**); 1594 (Ph of **1**), 483, 443, 404, 343 (νn Pt–Cl). ^{1}H-NMR (DMF): 7.91, 7.73, 7.56, 7.40, 7.21(m, Ph); 4.21(s, η-C_5H_5); 4.17, (η-C_5H_5,4), 10 (s, CH_2). ^{13}C-NMR (DMF, δ): 135.8; 134.3; 130.5; 130.4; 129.7; 126.6; 126.6; 71.8; 71.5; 69.3; 70.0; 68.9; 45.8. ^{195}Pt-NMR (DMF, δ) −2164, 2248. Λ (DMF) = 0. $Pt(PhCN)_2Cl_2$ (0.1 g, 0.22 mmol) with **6** (0.11 g, 0.44 mmol) was stirred 2 h at r.t. in 25 cm^3 benzene. The solvent was evaporated off and then washed with cold benzene, removing unreacted starting materials. The brown solid was dried and recrystallised from $CHCl_3$ to give brown crystals. Yield 0.05 g. Typically: Found: C, 49.9; H, 6.9; Cl, 11.6; N, 4.7%. IR (cm^{-1}); 2660. ^{1}H-NMR; 4.19(s, Fc); 4.06(s, CH_2); 2.62(s, CH_3).

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