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FULL PAPER

Tunable bis(ferrocenyl) receptors for the solution-phase electrochemical sensing of transition-metal cations

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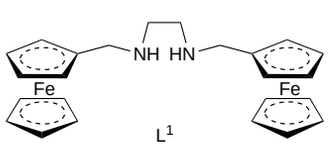
A series of linked bis(ferrocenyl) receptors with a variety of functionality in the spacer linkage was prepared, and their co-ordination properties with metal ions in non-aqueous solution were investigated. In particular, the ability of the ferrocene redox antenna to sense the binding of transition metals was monitored. The type of electrochemical response fell into two classes, dependent on both the metal ion investigated and the nature of the spacer group; the different receptor response mechanisms were assigned to either protonation or metal-ion co-ordination. Co-ordination and protonation therefore compete for this type of receptor in acetonitrile solution, and the affinity of the receptor and observed redox response are directly tunable.

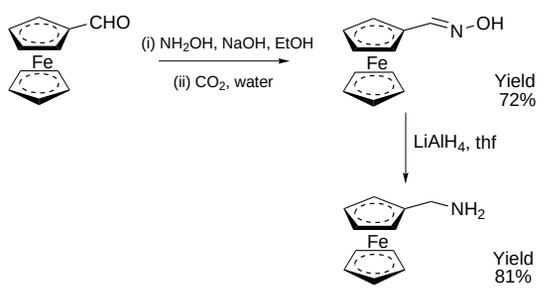
Transition-metal cations are essential in life processes, playing crucial roles at the active sites of many enzymes, with natural systems exhibiting exquisite control of metal-ion uptake, transport and storage.[1] This paper continues the reports of our research towards the development of electrochemical sensors for transition-metal cationic guests.[2] There is currently considerable interest in the development of sensors for a range of biologically important substrates.[3] One of the most attractive ways of achieving sensor design is to functionalise a receptor, capable of selective substrate binding with a metal centre, capable of reporting on the recognition event through a variety of physical responses.[4,5] Ferrocene is a particularly attractive functional antenna due to its relatively easy functionalisation coupled with its electrochemical and UV/VIS spectroscopic properties, which can be perturbed by the proximity of bound guests.[5] Initially, ferrocene-functionalised crown ethers and cryptands were synthesized, primarily for the recognition of alkali- and alkaline-earth metal cations.[6] More recently, however, research has begun to focus on the use of ferrocene-functionalised receptors for the recognition of more challenging guests, such as anions[2b,c,5,7d] and transition-metal cations.[2a,b,5b,7d,8]

In this paper a novel series of linked bis(ferrocenyl) receptors is reported and their redox response to a range of metal cations in non-aqueous solution discussed. In particular, two different types of electrochemical response were observed, corresponding either to *protonation* of the receptor or metal-ion *co-ordination*. This is, to the best of our knowledge, the first report of redox sensing of these different effects in non-aqueous solvent media. The factors controlling the balance of these two responses are discussed and particular emphasis is placed on the *tunability* of this type of receptor for transition-metal-ion binding.

A receptor of this type (L^1) has previously been reported by Neuse *et al.*[9] and further investigated by Martinez-Manez and co-workers[10] with platinum and copper complexes being isolated. The aim of our work, however, was to vary the nature of the spacer group between the (aminomethyl)ferrocene subunits, and in particular to investigate the tunability of the redox response, to bound guest ions in the solution phase.



L^1



Scheme 1 Synthesis of ferrocenylmethylamine

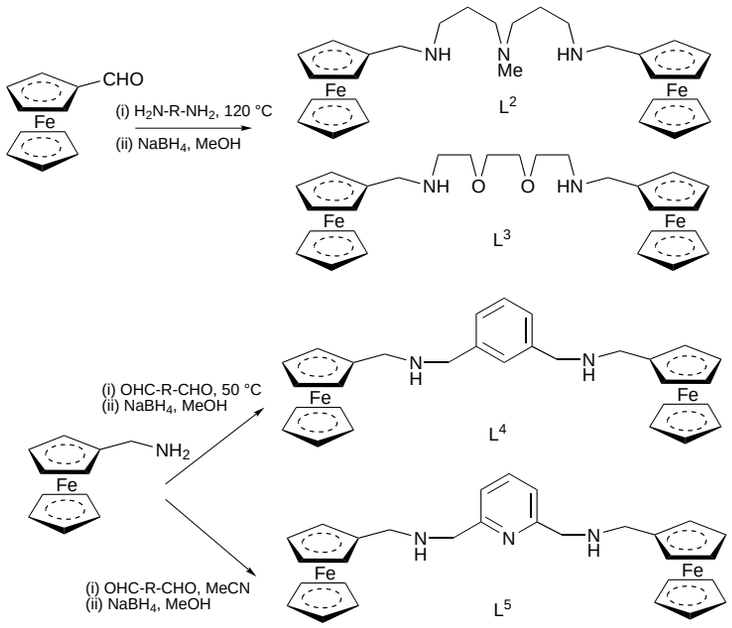
Results and Discussion

Syntheses

In order to synthesize linked bis(ferrocenyl) receptors, monosubstituted ferrocene synthons were required. Ferrocenecarbaldehyde was used both as a synthon in receptor synthesis and as a starting material for the synthesis of ferrocenylmethylamine (Scheme 1). Ferrocenecarbaldehyde was initially converted into its oxime by condensation with hydroxylamine in the presence of sodium hydroxide and subsequent protonation. Reduction to the amine was achieved by stirring with lithium aluminium hydride in tetrahydrofuran (thf) at room temperature. After aqueous work-up, pure ferrocenylmethylamine was isolated as a yellow solid in 81% yield.

Receptors L^2 and L^3 were synthesized from ferrocenecarbaldehyde, which reacts with amines under melt conditions (Scheme 2). In a typical reaction the aldehyde was melted at 120 °C, half an equivalent of diamine was added dropwise and the mixture stirred vigorously for 10 min. The crude Schiff-base product was reduced with an excess of sodium tetrahydroborate in methanol solution. The polyamine product was purified by extraction from water into dichloromethane and column chromatography on silica (MeOH–NH_4OH) to give L^2 and L^3 as semi-solid oils in 35 and 58% respective yields. In addition to the linked bis(ferrocenyl) products, small quantities of monoferrocenyl side products were obtained.

These receptors were characterised by ^1H and ^{13}C NMR spectroscopy, showing peaks in the ferrocene regions characteristic of a monosubstituted ferrocene subunit. Proton and carbon resonances for the co-ordinative portion of the receptor were more difficult to assign, however, due to the close similarity of a number of the atoms. This kind of problem was effectively addressed using two-dimensional correlated NMR



Scheme 2 Synthesis of a tunable series of bis-linked ferrocenyl receptors (L^2–L^5)

spectroscopy,[11] with modern gradient pulsed-field methods being especially useful due to their speed of acquisition.[12] Fast atom bombardment (FAB) mass spectroscopy was used further to characterise these products. Interestingly, during the course of this research, the FAB mass spectrometric properties of the Schiff-base precursors to these receptors were reported by Traldi and co-workers.[13] It was noted that the polyether-linked derivative showed more fragment peaks than the polyaza systems, due to its greater degree of chain cleavage. This effect was also observed in the mass spectrometric analysis of the polyamine receptors L^2 and L^3. This therefore confirms the validity of Traldi's analysis, with fragmentation being dependent on the spacer group and independent of whether it is attached to the ferrocenyl groups by Schiff-base or amine links.

Receptor L^4 was synthesized from the ferrocenylmethylamine precursor synthon by condensation with benzene-1,3-dicarbaldehyde. As such, it was the first linked bis(ferrocenyl) receptor to be synthesized using this reversal of reactive functionalities. Once again the synthesis was performed using melt methodology, only the reaction occurred at a lower temperature due to the lower melting point of ferrocenylmethylamine. Schiff-base reduction was once again performed using $NaBH_4$–MeOH (Scheme 2).

The pyridyl analogue L^5 was also synthesized. Pyridine-2,6-dicarbaldehyde was prepared from 2,6-bis(hydroxymethyl)-pyridine by oxidation with selenium dioxide. This bis-substituted heterocyclic aldehyde was then condensed with ferrocenylmethylamine in acetonitrile solution, rather than in a melt reaction. The product Schiff base precipitated from solution and reduction to the amine was achieved as before with $NaBH_4$. Receptor L^4, however, could not be synthesized using these solution-phase conditions. The apparent ease of synthesizing receptor L^5 is, however, somewhat puzzling, as pyridine aldehydes usually show similar reactivity to their benzene analogues.[14] These receptors were characterised by proton and carbon NMR, FAB mass spectrometry and elemental analysis.

Co-ordination studies of linked bis(ferrocenyl) receptors

Repeated attempts were made to isolate various transition-metal-ion complexes of these receptors in the solid phase. They were, however, unsuccessful and consequently the co-ordination properties of these receptors in solution was thoroughly investigated. Of particular interest is the ability of these systems to show a redox response on the co-ordination of metal ions. This effect can form the basis of ion sensors and switches and consequently solution-phase electrochemical co-ordination experiments were of primary interest.

Table 1 Electrochemical behaviour of the ferrocene redox wave of receptors L^2–L^5 in acetonitrile with and without protonation. All $E_{\frac{1}{2}}$ values are relative to Ag^+–Ag in MeCN and are accurate to ±5 mV

	$E_{\frac{1}{2}}$/V		
Receptor	ferrocene	With H^+	$\Delta E(H^+)$/mV
L^2	≈0.05 *	0.210	160
L^3	0.027	0.193	166
L^4	0.040	0.200	160
L^5	0.030	0.186	156

* Broad oxidation peak.

Electrochemical studies

Cyclic[15] and square-wave[16] voltammetries were used to investigate the reversibility of the ferrocenium–ferrocene redox couple. The redox potential for each of the receptors L^3–L^5 was measured in acetonitrile solution, with all the receptors showing a quasi-reversible redox wave with a half potential of approximately 0.035 V (Table 1). This is the ferrocene redox couple, which appears as a single wave, indicating that the two ferrocene groups are electrochemically independent of one another. The similarity of redox potential for each of the receptors can be rationalised by the equivalent environment of the ferrocene subunit in each case. A small separate amine oxidation wave was observed at more anodic potentials than that of the ferrocene couple. The exception to the single-wave quasi-reversible ferrocene redox behaviour was receptor L^2, which exhibited a very broad oxidation peak (≈0.1–0.2 V), probably due to the interference of tertiary amine oxidation processes.

The behaviour of the receptors in the presence of HBF_4 was also investigated, the effect of this strong acid being protonation of the amine nitrogen atoms (Table 1). In each case the cyclic voltammogram became fully reversible, with no subsidiary amine oxidations being observed (as the lone pair binds the proton). The redox potential of the ferrocene nucleus was shifted anodically, by approximately 160 mV in each case. Amine protonation builds up positive charge close to the ferrocene nucleus and this electrostatically repels the ferro-

Table 2 Electrochemical shifts (mV) of the ferrocene redox couple in acetonitrile on the addition of metal salts as hydrated perchlorates/tetrafluoroborates (n.i. = not investigated). In each case the electrochemical response corresponds to either protonation or binding

	Metal salt				
Receptor	Ni^{II}	Cu^{II}	Zn^{II}	Ca^{II}	Pb^{II}
L^2	58 Co-ordination	98 Co-ordination	162 Protonation	n.i.	n.i.
L^3	73 Co-ordination	160 Protonation	168 Protonation	172 Protonation	165 Protonation
L^4	175 Protonation	169 Protonation	n.i.	160 Protonation	n.i.
L^5	115 Co-ordination	105 Co-ordination	75 Co-ordination	158 Protonation	n.i.

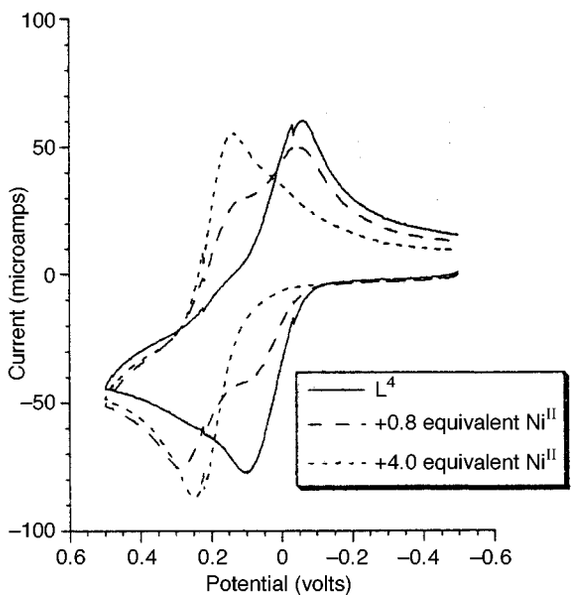


Fig. 1 Cyclic voltammogram of receptor L^4 and the effect of nickel(II) perchlorate addition (protonation-type response)

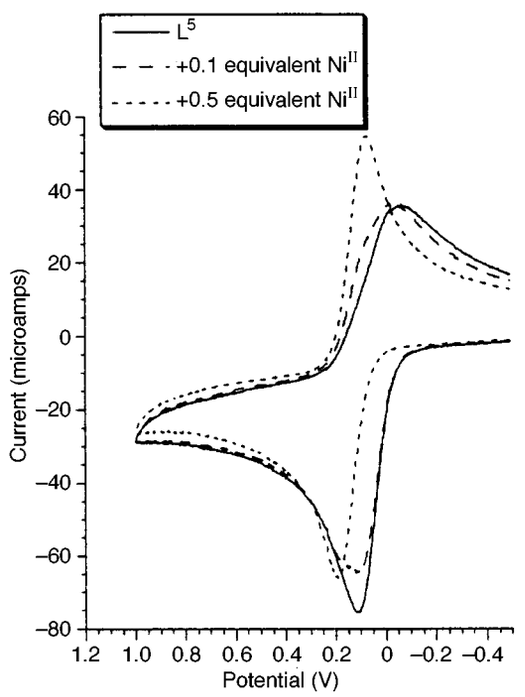


Fig. 2 Cyclic voltammogram of receptor L^5 and the effect of nickel(II) perchlorate addition (co-ordination-type response)

cenium cation through space, thermodynamically hindering its formation. The protonation-induced redox shift is similar for all these receptors due to the equivalence of the ferrocene group environment in each case.[17]

The magnitude of electrochemical shift on protonation can be used to provide important thermodynamic information. The shift in redox potential on protonation is related to the ratio of protonation constants for the oxidised and reduced forms of the receptor. For the receptors being considered, the average potential shift on protonation was 160 mV and consequently K_{ox}/K_{red} (the binding enhancement factor) is approximately equal to 1.79×10^{-3}. This means that it is 560 times more difficult to protonate the oxidised form of the receptor than the reduced form.

The effect of metal ions on receptor redox chemistry was then investigated (Table 2). The metals ions studied have two relevant properties in non-aqueous solution: (a) co-ordination, suitable metal ions can be co-ordinated by the receptor species and (b) acidity, metal ions can protonate the receptor due to the use of hydrated metal perchlorate salts with ionisable protons. It is therefore of great importance clearly to establish in each case whether co-ordination or protonation effects are being observed.

Receptors L^4 and L^5 illustrate the importance of considering protonation effects in combination with metal-ion binding. The addition of nickel(II) perchlorate in acetonitrile, for example, elicited different responses from each of the receptors. For receptor L^4 a new redox wave evolved on nickel(II) addition, which was shifted 175 mV anodically from the original ferrocene redox potential (Fig. 1). Receptor L^5, however, showed a smaller perturbation of the redox wave (115 mV), which shifted continuously on metal-ion addition (Fig. 2).

The evolving peak in the electrochemical study of receptor L^4 directly corresponds to the redox wave of the protonated receptor, with addition of HBF_4 to the final solution causing no further change in the redox behaviour. Binding studies performed with copper(II) and calcium(II) (a hard metal ion which should not bind to the receptor in any case) both showed exactly the same response with evolution of a new redox wave. Consequently for receptor L^4 it is likely that co-ordination-type behaviour is not observed electrochemically, and that protonation-type behaviour is dominant.

In the case of receptor L^5, however, the redox wave resulting from the addition of nickel perchlorate did not correspond to that of the protonated receptor. Addition of HBF_4 to the resultant electrochemical solution *did* elicit a further redox response, with the evolution of a new redox wave for the protonated receptor. It can therefore be concluded that metal-ion co-ordination is observed in this case. Further evidence for this co-ordination is also available; copper(II) and zinc(II) ions both elicited similar redox shifts to that of nickel(II), whilst calcium(II) (a hard metal ion which should have a poor co-ordination affinity for the receptor) exhibited typical protonation behaviour, with the evolution of a new highly shifted reversible redox wave ($\Delta E \approx 160$ mV).

It is noteworthy that the redox shift corresponding to proto-

Table 3 Summary of electrochemical sensing behaviour showing the tunability of response. ✓ Indicates metal binding response, ✗ indicates protonation response

	Metal ion		
Receptor	Ni^{II}	Cu^{II}	Zn^{II}
L^5	✓	✓	✓
L^2	✓	✓	✗
L^3	✓	✗	✗
L^4	✗	✗	✗

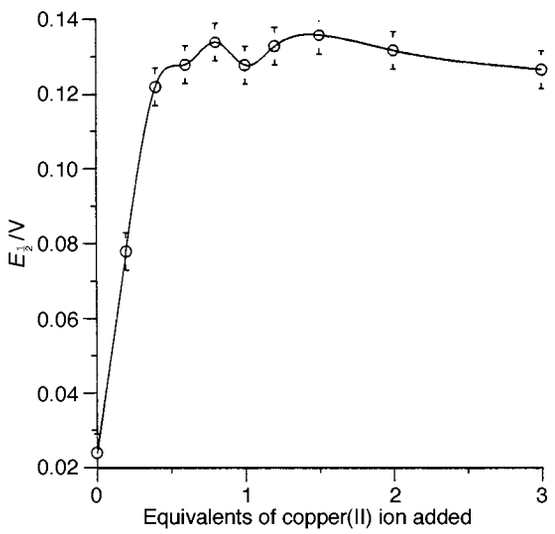


Fig. 3 Electrochemical titration curve for receptor L^5 with copper(II) indicating a 2:1 (receptor:metal ion) stoichiometry

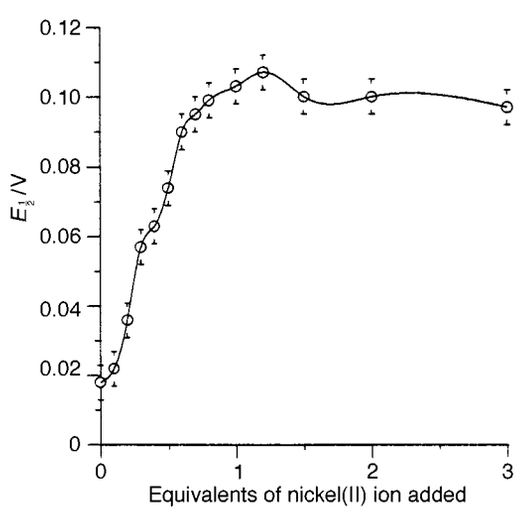


Fig. 4 Electrochemical titration curve for receptor L^3 with nickel(II) indicating a 1:1 binding stoichiometry

nation is larger than that for co-ordination. This is because on protonation each individual positive charge is localised close to a ferrocene redox centre, whereas on metal-ion co-ordination the dipositive charge of the metal ion is bound by a combination of the donor atoms, more distant from the ferrocene groups, and consequently perturbing them less.

Consequently, it is proposed that in these electrochemical experiments a subtle balance between co-ordination and protonation equilibrium behaviour is observed. If the receptor is inefficient, such as L^4 with its large donor atom bite angle, then co-ordination is thermodynamically inhibited and protonation is observed instead. For a more effectively organised receptor, such as L^5 with its additional pyridine donor nitrogen atom, metal co-ordination dominates. The metal ion must, however, be suitable for binding, the hydrated calcium(II) cation showing simple protonation behaviour.

The evolving half potential of the ferrocene couple L^5 relative to the amount of metal ion added was followed during the metal co-ordination experiments, yielding titration curves. The addition of half an equivalent of metal(II) ions gave the maximum redox shift, providing evidence that the solution complex species has 1:2 (metal ion:receptor) stoichiometry (Fig. 3). This indicates that with three donor atoms each, two receptor molecules can bind to one transition-metal ion, as would indeed be expected for a six-co-ordinate solution complex.

Further evidence for a thermodynamic balance between protonation and binding processes was provided by receptors L^2 and L^3, with the addition of different metal ions once again yielding different responses (Table 2). Receptor L^2 showed different behaviour with different transition-metal cations, giving co-ordinative behaviour with Cu^{II} and Ni^{II}, whilst showing protonation behaviour with Zn^{II}. This indicates that the binding strength of zinc ions to this receptor is not sufficient to counteract its relatively high acidity and prevent the observation of protonation behaviour. For receptor L^3 the equilibria appear to lie even more strongly in favour of protonation, with Cu^{II} also showing protonation-type behaviour. In fact, only nickel(II) ions were electrochemically observed to bind to this receptor in acetonitrile solution. The titration curve interestingly showed 1:1 stoichiometry (Fig. 4), providing evidence that the tetradentate donor group disfavours the co-ordination of two receptors to one metal centre (unlike the tridentate receptor L^5). Lead(II) and Ca^{II} were also studied to see whether they formed preferential interaction with the hard oxygen donor groups present in the receptor, but in fact simple protonation-type behaviour was observed.

For the first time, care has been taken to isolate *protonation* and *co-ordination* effects in the solution phase, and their thermodynamic balance in this type of system has been clearly illustrated by variation of both receptor donor group and metal ion. Table 3 summarises in a clear visual form which combination of receptor and transition-metal ion shows an electrochemical binding response and which a protonation response. The observation of an unequivocal binding response is dependent on both *receptor structure* and the *metal ion* being investigated, making these receptors a tunable series of transition-metal-selective redox sensors.

Nuclear magnetic resonance studies

The NMR titration studies are particularly suitable for investigating the binding of diamagnetic zinc(II) ions yielding additional information about the recognition event. Proton NMR titrations in acetonitrile were therefore performed on receptors L^3 (*protonation* behaviour) and L^5 (*co-ordination* behaviour) for comparison. Receptor L^3 yielded sharp titration profiles with the continuous shift in NMR peaks indicating fast equilibria on the NMR time-scale. Following the ferrocenyl protons, the stoichiometry of protonation clearly appears to be 1:1 (Fig. 5). When considering the alkyl protons proximate to the donor atoms, however, the situation can be understood more fully (Fig. 6). As would be expected, the protons next to the nitrogen atoms are more markedly perturbed than those next to the oxygen atoms, due to the build up of adjacent positive charge on the protonated nitrogen centres. The binding curves for the CH_2N protons are typical of a mixture of 1:2 and 1:1 stoichiometries. This would be expected, as there are two nitrogen atoms in the receptor, each of which can gain a proton. Receptor L^5, however, showed markedly different (*co-ordination* type) behaviour. Following the aromatic peaks during the titration, new NMR peaks evolved whilst the old peaks decreased in intensity. The evolution of new peaks (as opposed to peak shifting) indicates either thermodynamically strong or

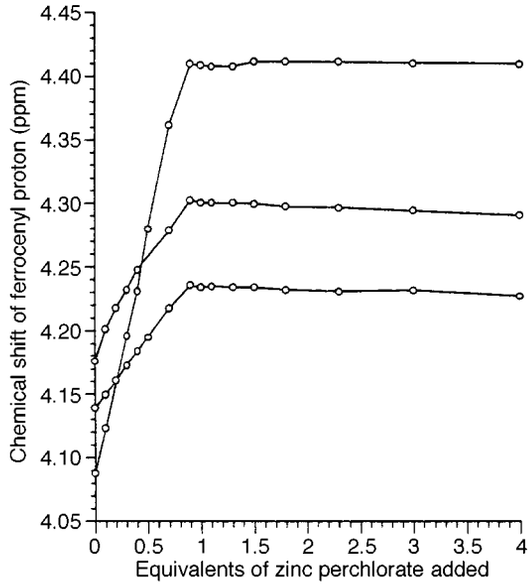


Fig. 5 Proton NMR titration curves following ferrocenyl protons for the titration of L^3 with zinc(II)

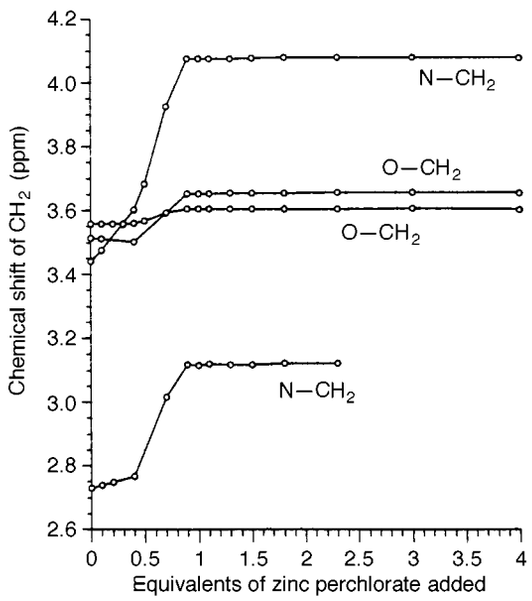


Fig. 6 Proton NMR titration curves following CH_2 protons for the titration of L^3 with zinc(II)

kinetically slow binding. Two different complex species were observed, although it was difficult to draw accurate conclusions about binding stoichiometries. The difference in NMR behaviour between receptor L^3 and receptor L^5 provides further evidence supporting the different protonation and co-ordination mechanisms as proposed from electrochemical investigation.

UV/VIS spectroscopic studies

In addition to its redox activity, ferrocene has UV/VIS spectroscopic properties which can readily be monitored. Titration investigations were performed in acetonitrile solution, and once again there was a sharp contrast between *protonation* and *co-ordination* behaviour.

The UV/VIS spectrum of free receptor L^5 shows a d–d band at a wavelength of 438 nm. On addition of copper(II) ions this d–d band increased in intensity and shifted 29 nm to longer wavelength. A new asymmetric band at 630 nm formed after the receptor saturation point, probably corresponding to the Jahn–Teller-distorted d–d band for uncomplexed copper(II) ions. On extracting the intensity at 440 nm during the titration, the titration curve obtained indicated 1:2 (metal ion:receptor) stoichiometry, concurring with electrochemical results (*co-ordination* behaviour). Receptor L^4, however, showed different UV/VIS behaviour, with the ferrocene d–d band becoming swamped by the charge-transfer band. The direction of its shift on protonation could not, therefore, be ascertained and on intensity extraction no titration profile was obtained (*protonation* behaviour). Receptor L^3 also showed similar protonation-type behaviour on the addition of copper(II) tetrafluoroborate.†

Conclusion

Co-ordination studies were performed in solution in order to investigate the kinetic and thermodynamic properties of the co-ordination process. Addition of metal ions was found to give rise to two different types of response. By comparison with the effect of acid on the receptors, these responses were assigned as either *protonation* or *co-ordination type*. The redox potential (and UV/VIS properties) of the ferrocene subunit was shown to respond differently to both these processes. If the strength of co-ordination was enhanced, for example by using a receptor with a more effectively organised donor set, then co-ordination was more likely to be observed. If the metal ion was 'hard' and less suitable for binding by polyaza donors then protonation was more likely to be observed.

For the first time, care has been taken to isolate *protonation* and *co-ordination* effects in the solution phase, and their thermodynamic balance in this type of system has been clearly illustrated by variation of both receptor donor group and metal ion. In this way, these four receptors form a tunable series of transition-metal-selective redox sensors. This work therefore emphasises the importance of the proton, even in non-aqueous solvents, and complements our research targetting the development of water-soluble polyaza redox sensors which are pH tunable.[2b,c] Protons and transition-metal ions play key roles in biological processes, and the differentiation of protonation and co-ordination responses caused by metal-ion guests through the use of a simple redox antenna is unprecedented.

Experimental

Where necessary, solvents were purified prior to use and stored under nitrogen. Tetrahydrofuran was distilled from sodium using benzophenone as a moisture indicator. Acetonitrile was predried over class 4 Å molecular sieves (4–8 mesh) and then distilled under nitrogen from calcium hydride. Unless otherwise stated in the text, commercial grade chemicals were used without any further purification. Ferrocenecarbaldehyde oxime[19] and pyridine-2,6-dicarbaldehyde[20] were prepared by literature procedures and showed analytical data consistent with their proposed structures.

The NMR spectra were recorded on either a Bruker AM 300 instrument or a Varian Unity Plus 500 machine. The Bruker spectrometer operates at 300 MHz for ^1H and 75.47 MHz for ^{13}C NMR, the Varian spectrometer at 500 MHz for ^1H and 125.7 MHz for ^{13}C. In both cases, the solvent deuterium signal was used as internal reference. Correlated NMR experiments using pulsed field gradients were used to assist in characterisation. Elemental analyses were carried out by the Inorganic Chemistry Laboratory Microanalysis Service. Fast atom bombardment (FAB) mass spectrometry was performed at the University College of Swansea by the EPSRC service. Ultraviolet–visible spectrometry was carried out on a Perkin-Elmer Lambda 6 UV/VIS spectrophotometer. Electrochemical measurements were conducted on a Princeton Applied

† After submission of this paper the protonation and transition-metal electrochemical recognition studies of a related *N*-methyl analogue of L^3 were reported.[18]

Research Model 273 potentiostat/galvanostat. The working electrode was glassy carbon, the counter electrode platinum wire and the reference electrode Ag^+–Ag (in MeCN).

Syntheses

Ferrocenylmethylamine. Ferrocenecarbaldehyde oxime (2.25 g, 9.83 mmol) was dissolved in dry thf (80 cm^3) and an excess of lithium aluminium hydride (1.7 g, 44.8 mmol) was added portionwise with care. The mixture was stirred under nitrogen for 6 h. Benzene (80 cm^3) was added to the solution followed by ethyl acetate (15 cm^3) added with caution. A few drops of 5 M NaOH were then added until precipitation of inorganics was complete. The mixture was filtered yielding a yellow filtrate and a gummy solid residue. The residue was washed with copious amounts of benzene–methanol (80 : 20). The filtrate was then evaporated to dryness and inorganic impurities removed by dissolution in dichloromethane followed by filtration and evaporation of the organic filtrate. The product was, if necessary, further purified by column chromatography on silica using MeOH–NH_4OH (95 : 5) as eluent. Yield 81% (1.71 g, 7.96 mmol). ^{1}H NMR ($CDCl_3$): δ 4.15 (9 H, m, ferrocenyl H), 3.54 (2 H, s, $C_5H_4CH_2$) and 1.44 (2 H, br s, NH) (Found: C, 61.18; H, 5.76; N, 6.45. Calc. for $C_{11}H_{13}FeN$: C, 61.43; H, 6.09; N, 6.51%).

***N*,*N*′-Bis(ferrocenylmethyl)-3,3′-(methylimino)dipropylamine (L^2).** Ferrocenecarbaldehyde (0.5 g, 2.34 mmol) was taken in an Erlenmeyer flask (25 cm^3) and melted on an oil-bath (120 °C). Half an equivalent of 3,3′-(methylimino)dipropylamine (0.18 g, 1.17 mmol) was added dropwise to the stirring melt and the mixture left to stir for 10 min. Water vapour was produced as the condensation reaction occurred. The mixture was then cooled. The product solid was suspended in methanol (30 cm^3) and an excess of $NaBH_4$ (0.5 g, 13.16 mmol) added portionwise with stirring under nitrogen. The mixture was stirred for 2 h and then rotary evaporated to dryness. The residue was dissolved in water (30 cm^3) and extracted with chloroform (3 × 40 cm^3). The organic extracts were then dried over $MgSO_4$ and rotary evaporated to dryness. The product was purified by column chromatography on SiO_2 using gradient elution with MeOH–NH_4OH solvent mixes. Yield 35% (0.24 g, 0.44 mmol). A small amount (0.03 g, 0.08 mmol) of the monoferrocene-substituted material was obtained as side product. ^{1}H NMR ($CDCl_3$): δ 4.19–4.13 (18 H, m, ferrocenyl H), 3.52 (4 H, s, $C_5H_4CH_2$), 2.66 (4 H, t, J = 6.89, NCH_2), 2.38 (4 H, t, J = 7.07, NCH_2), 2.21 (3 H, s, NCH_3), 1.63 (6 H, m, J = 6.93, CCH_2C and NH). ^{13}C NMR ($CDCl_3$): δ 86.64 (ferrocenyl *C*C), 68.41 (ferrocenyl CH), 67.75 (ferrocenyl CH), 56.07 (NC), 49.06 (NC), 48.08 (NC), 42.33 (NC) and 27.54 (CCH_2C). FAB mass spectrum: *m*/*z* 542, $[M + H]^+$; 199, $[(C_5H_5)Fe(C_5H_4CH_2)]^+$; and 121, $[Fe(C_5H_5)]^+$.

***N*,*N*′-Bis(ferrocenemethyl)-2,2′-(ethylenedioxy)diethylamine (L^3).** As above, melt conditions were used to treat ferrocenecarbaldehyde (0.75 g, 3.51 mmol) with half an equivalent of the diamine (0.26 g, 1.75 mmol). Reduction and purification were as above. Yield 58% (0.59 g, 1.08 mmol). A small quantity of monoferrocenyl side product was once again obtained. ^{1}H NMR ($CDCl_3$): δ 4.16 (4 H, s, ferrocenyl H), 4.11 (10 H, s, ferrocenyl *H*), 4.07 (4 H, s, ferrocenyl H), 3.57 (4 H, s, $C_5H_4CH_2$), 3.55 (4 H, t, J = 4.96, NCH_2), 3.46 (4 H, s, OCH_2CH_2O), 2.78 (4 H, t, J = 5.06 Hz, OCH_2CH_2N) and 1.7 (2 H, br s, NH). ^{13}C NMR ($CDCl_3$): δ 86.87 (ferrocenyl *C*C), 70.21 (CN), 70.09 (CN), 68.16 (ferrocenyl CH × 2), 67.44 (ferrocenyl CH), 48.77 (CO) and 48.59 (CO). FAB mass spectrum: *m*/*z* 567, $[M + Na]^+$; 545, $[M + H]^+$; 544, M^+; 479, $[M - C_5H_5]^+$; 345, $[M - (C_5H_5)Fe(C_5H_4CH_2)]^+$; 303, $[(C_5H_5)Fe(C_5H_4)CH_2NH(CH_2)_2O(CH_2)_2OH]^+$; 199, $[(C_5H_5)Fe(C_5H_4CH_2)]^+$ and 121, $[Fe(C_5H_5)]^+$.

***N*,*N*′-Bis(ferrocenemethyl)-1,3-bis(aminomethyl)benzene (L^4).** Ferrocenylmethylamine (0.25 g, 1.21 mmol) and 1,3-bis(aminomethyl)benzene (0.078 g, 0.6 mmol) were warmed together in a hot water-bath in the presence of no solvent with vigorous stirring. After 10 min the mixture was cooled, methanol added and an excess of $NaBH_4$ (0.25 g, 6.58 mmol) added portionwise to the stirring suspension. The mixture was stirred for 3 h and then rotary evaporated to dryness. The residue was dissolved in water (30 cm^3) then extracted with chloroform (3 × 20 cm^3). The organic extracts were combined, dried over $MgSO_4$ and evaporated to dryness. Purification was performed by column chromatography on silica using MeOH–NH_4OH (95 : 5) as eluent. Yield 27% (0.085 g, 0.16 mmol). A small amount (20%, 0.040 g, 0.12 mmol) of monoferrocenyl side product was obtained. ^{1}H NMR ($CDCl_3$): δ 7.31–7.22 (4 H, m, aryl-H), 4.19–4.11 (18 H, m, ferrocenyl-H), 3.82 (4 H, s, $C_6H_4CH_2$), 3.54 (4 H, s, $C_5H_4CH_2$) and 1.70 (2 H, br s, NH). ^{13}C NMR ($CDCl_3$): δ 140.6 (arylC-C), 128.5 (arylCH), 127.8 (arylCH), 126.7 (arylCH), 86.97 (ferrocenyl*C*C), 68.43 (ferrocenylCH × 2), 67.76 (ferrocenyl*C*H), 53.37 (CH_2) and 48.34 (CH_2) (Found: C, 64.74; H, 5.77; N, 4.93. Calc. for $C_{30}H_{32}Fe_2N_2 \cdot 0.33CH_2Cl_2$: C, 65.03; H, 5.82; N, 5.00%). FAB mass spectrum: *m*/*z* 532, M^+; 199, $[(C_5H_5)Fe(C_5H_4CH_2)]^+$ and 121, $[Fe(C_5H_5)]^+$.

***N*,*N*′-Bis(ferrocenemethyl)-2,6-bis(aminomethyl)pyridine (L^5).** Ferrocenylmethylamine (0.3 g, 1.45 mmol) was dissolved in dry acetonitrile (15 cm^3) and added dropwise to a stirred solution of pyridine-2,6-dicarbaldehyde (0.094 g, 0.72 mmol) also in MeCN (5 cm^3). The mixture was stirred and after half an hour a precipitate formed. After a further half hour the solvent was removed by rotary evaporation. The residue was suspended in methanol (20 cm^3) and $NaBH_4$ (0.3 g, 7.90 mmol) was added portionwise, with stirring, under nitrogen. After 1 h the reaction was evaporated to dryness. Water (30 cm^3) was added and the product extracted into dichloromethane (3 × 30 cm^3). The organics were combined and evaporated to dryness yielding the product that required no further purification. Yield 94% (0.37 g, 0.68 mmol). ^{1}H NMR ($CDCl_3$): δ 7.59 (1 H, t, aryl H), 7.16 (2 H, d, aryl H), 4.20 (4 H, s, ferrocenyl H), 4.13 (10 H, s, ferrocenyl H), 4.09 (4 H, s, ferrocenyl H), 3.93 (4 H, s, $NC_5H_3CH_2N$), 3.53 (4 H, s, $C_5H_4CH_2N$) and 2.16 (2 H, br s, NH). ^{13}C NMR ($CDCl_3$): δ 159.4 (aryl *C*C), 136.8 (aryl CH), 120.4 (aryl CH), 87.06 (ferrocenyl *C*C), 68.44 (ferrocenyl CH), 68.35 (ferrocenyl CH), 67.72 (ferrocenyl CH), 54.62 (CH_2) and 48.54 (CH_2) (Found: C, 61.12; H, 5.63; N, 7.31. Calc. for $C_{29}H_{31}Fe_2N_3 \cdot 0.5CH_2Cl_2$: C, 61.54; H, 5.60; N, 7.30%). FAB mass spectrum: *m*/*z* 533, M^+.

Electrochemical investigations

Typically, receptor (1×10^{-5} mol) was dissolved in solvent (5 cm^3) and tetrabutylammonium tetrafluoroborate (base electrolyte) (0.16 g) added. The guest under investigation was then added as a 0.1 M solution using a microsyringe whilst the cyclic and square-wave voltammetric properties of the solution were monitored. To maintain reversibility, the working electrode was polished between scans (using diamond polish) to remove adsorbate from the glassy carbon surface.

Proton NMR titrations

Proton NMR titrations were performed by dissolving receptor (5×10^{-6} mol) in CD_3CN (0.5 cm^3) in an NMR tube. The guest being investigated was then added as a 0.1 M solution using a microsyringe in order to add substoichiometric quantities whilst the NMR spectrum of the receptor was monitored.

UV/VIS spectrometric studies

Typically receptor (2.5×10^{-6} mol) was dissolved in acetonitrile (2.5 cm^3) (ionic strength 0.1 M made up with base

electrolyte) and placed in a quartz cuvette. Once again the guest was added using a microsyringe (as a 0.1 M solution).

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