A Potassium-selective Sulfide-linked Redox-active Ferrocene Ionophore that exhibits Extraordinary Electrochemical Recognition Behaviour

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A new ferrocenyl ionophore $\mathbf{L}^1$ selectively complexes, electrochemically recognises and responds to, *via* an extraordinary cathodic perturbation of the metallocene redox centre, the potassium guest cation in the presence of equimolar amounts of sodium ions.

The electrochemical recognition of charged guest species by redox-active ionophores is an area of intense current interest of relevance to the advancement of chemical sensor technology.[1] These ligand systems can be designed to be redox responsive to the binding of metal and ammonium cations as well as anionic guest species such as halides, nitrate and phosphate.[2,3] In an effort to ultimately produce a prototype group 1 selective amperometric sensor we have incorporated the ferrocene redox-active moiety into bis(crown ether) ligand frameworks and shown that the vinyl linked compound **1** selectively electrochemically recognises the potassium cation in the presence of sodium and magnesium ions.[4]

With a view to amplifying this electrochemical recognition effect by seeking a more efficient electrostatic communication between the redox centre and crown ether bound cationic guest we report here a new potassium-selective sulfide-linked ferrocene ionophore that exhibits extraordinary electrochemical recognition behaviour.

The reaction of ferrocene with 2 equiv. of *n*-butyllithium in hexane, in the presence of *N,N,N′,N′*-tetramethylethylenediamine (TMEDA) produced the 1,1′-bis lithiated ferrocene compound **2** as an orange precipitate. 4,4′-Bis(benzo-15-crown-5)-disulphide **3**[5] in dry tetrahydrofuran (THF) was added to the suspended lithiated solution and the new ferrocenyl ionophore $\mathbf{L}^1$ was isolated after column chromatography as a yellow solid (m.p. 109–110 °C) in 37% overall yield. (Scheme 1). Monolithiated ferrocene was prepared *via* the reaction of 1 equiv. of *n*-butyllithium with ferrocene and addition of **3** in an analogous preparative procedure gave $\mathbf{L}^2$ as a yellow solid (m.p. 78–80 °C) in 23% yield (Scheme 1). Satisfactory elemental analyses, FABMS, and ^{1}H and ^{13}C NMR spectroscopy characterised both new ligands.

Refluxing acetonitrile solutions of $\mathbf{L}^1$ and $\mathbf{L}^2$ with sodium and potassium hexafluorophosphate salts led to the isolation of yellow complexes of respective stoichiometries $[\mathbf{L}^1\cdot 2\mathrm{Na}](\mathrm{PF}_6)_2$, $[\mathbf{L}^1\cdot \mathrm{K}]\mathrm{PF}_6$, $[\mathbf{L}^2\cdot \mathrm{Na}]\mathrm{PF}_6$ and $[(\mathbf{L}^2)_2\cdot \mathrm{K}]\mathrm{PF}_6$. The same stoichiometries were determined from solution ^{13}C NMR titration experiments in acetonitrile and also observed in the respective fast atom bombardment mass spectra of the complexes. These results suggest that $\mathbf{L}^1$ forms a 1 : 2 ligand to the metal complex with sodium cations, indicating that the two benzo crown ether moieties are acting independently, each complexing a sodium cation whereas the larger potassium cation forms a 1 : 1 intramolecular sandwich complex with $\mathbf{L}^1$ in which the crown ethers are acting cooperatively. (Fig. 1). Ligand $\mathbf{L}^2$ possessing only one crown ether moiety complexes one sodium cation, however; with potassium a 2 : 1 ligand to metal intermolecular sandwich complex is produced. (Fig. 1).

The electrochemical properties of $\mathbf{L}^1$, $\mathbf{L}^2$ and model compounds **4** and **5**, prepared *via* analogous synthetic routes to $\mathbf{L}^1$ and $\mathbf{L}^2$, were investigated by cyclic voltammetry in anhydrous acetonitrile using $[\mathrm{Bu^n{}_4N}]\mathrm{BF}_4$ as the supporting electrolyte. The cyclic voltammograms were also recorded after addition of calculated equivalents of Na^+ and K^+, and equimolar mixtures of $\mathrm{Na}^+/\mathrm{K}^+$; see Table 1. All the new compounds exhibited reversible one-electron oxidation electrochemistry with potentials *vs* saturated calomel electrode (SCE) ranging from 0.49 to 0.58 V, typical for ferrocene containing derivatives.

With the sodium cation, one-wave anodic shifts in the respective redox potential of the ferrocenyl redox couple of $\mathbf{L}^1$ and $\mathbf{L}^2$ occur as a result of the electrostatic inductive effect of the crown ether bound sodium cation withdrawing electron density from the ferrocene moiety, thus increasing the observed oxidation potential. It is noteworthy that the magnitude of the Na^+-induced anodic shift of $\mathbf{L}^1$ (70 mV) is approximately double the observed cation-induced perturbation with the mono crown ether ligand $\mathbf{L}^2$ (30 mV) in agreement with the stoichiometric findings discussed above. The addition of potassium cations to electrochemical solutions of $\mathbf{L}^2$ produced an expected one-wave anodic perturbation of comparatively smaller magnitude to the Na^+ electrochemical

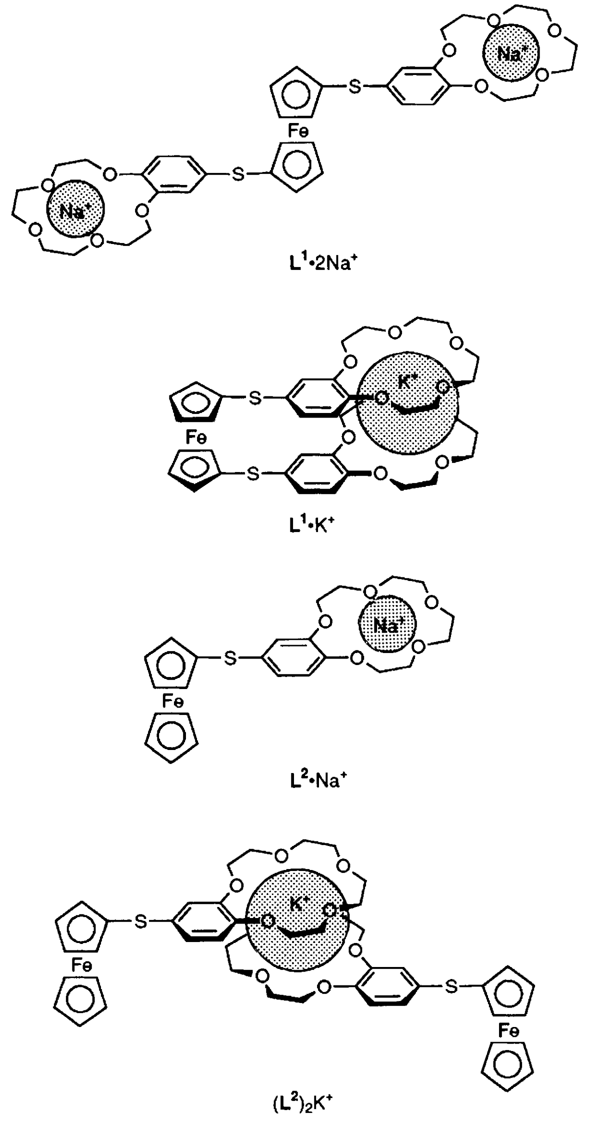
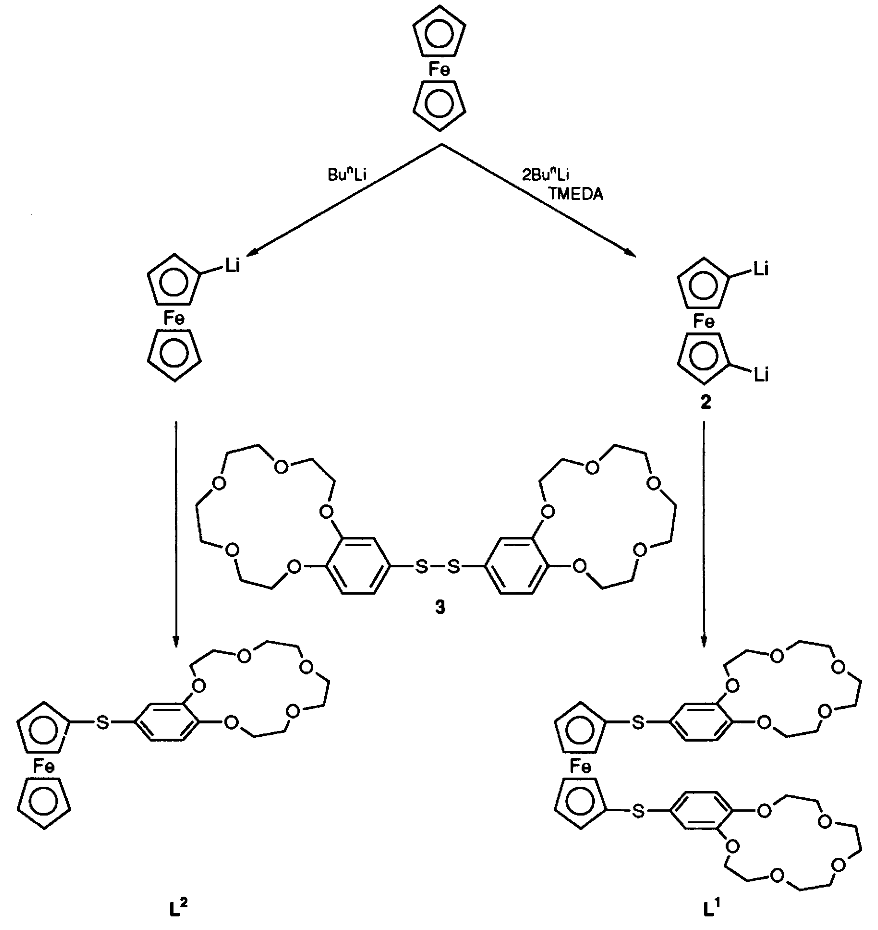
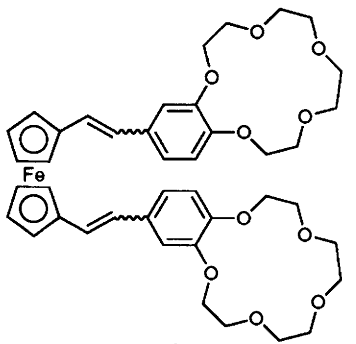


Fig. 1 Schematic representations of the sodium and potassium complexes of $\mathbf{L}^1$ and $\mathbf{L}^2$



Scheme 1



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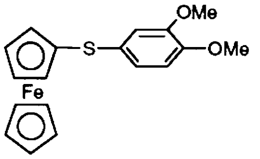

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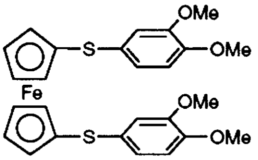

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recognition result, a consequence of the sodium cation possessing a higher charge density than K^+. However, analogous K^+ electrochemical recognition experiments with L^1 gave surprisingly unexpected and unprecedented results. The addition of potassium cations did not lead to the predicted anodic shift but resulted in a cathodic perturbation of 60 mV of the ferrocenyl redox couple, (Table 1). This observation suggests that in some way the presence of the positively charged K^+ increases unexpectedly the electron density at the ferrocene redox centre of L^1. After studying molecular models (CPK) of the free ligand and potassium metal complex a possible rationalisation for this extraordinary electrochemical recognition behaviour may centre around the role of the sulfur atoms of L^1. As discussed above, L^1 forms a 1:1 intramolecular bis benzo crown ether sandwich complex with potassium and in doing so brings the two sulfur atoms of the respective cyclopentadienyl rings close together. Consequently, this may force the two sulfur atoms' lone pairs of electrons close enough to cause repulsion and compel the lone pairs to adopt a conformation, which directs electron density towards the ferrocene redox centre. This would then make the ferrocenyl moiety easier to oxidise resulting in the observed cathodic shift. With Na^+ the usual anodic shift is detected with L^1 because the crown ether coordinating units are acting in an independent fashion binding one Na^+ in each crown ether resulting in no steric constraint being placed upon the sulfur atoms. Similarly, the sulfur atoms do not come into close proximity in the intermolecular $K^+:2L^2$ sandwich complex and thus the anticipated anodic shift is observed.

The addition of sodium or potassium cations to electrochemical solutions of **4** and **5** led to negligible changes ($\Delta E \leqslant 5$ mV) in the positions of the respective redox couples suggesting L^1 and L^2 complex these cations exclusively via the crown-ether coordinating units.

We believe that this is the first time that cation guest electrochemical recognition by a ferrocene redox-active ionophore gives rise to a cathodic shift in the metallocene's redox couple and sets a precedence for the future design of amperometric sensors based on conformational preferences of the target guest species.

Table 1 Electrochemical data

Compound	L^1	L^2	**4**	**5**
$E_{1/2}/V$[a]	0.54	0.49	0.58	0.55
ΔEp/mV[b]	80	70	110	90
$\Delta E(Na^+)$/mV[c]	70	30	<10	<10
$\Delta E(K^+)$/mV[c]	−60	20	<10	<10
$\Delta E(Na^+/K^+)$/mV[d]	−60	—	—	—

[a] Obtained in acetonitrile containing 0.2 mol dm^{-1} ($Bu^n_4BF_4$) as supporting electrolyte. Solutions were *ca.* 2 × 10^{-3} mol dm^{-3} in compound and potentials were determined with reference to a SCE. [b] Separation between anodic and cathodic peak potentials of cyclic voltammograms; values for ferrocene under the same conditions ranged from 70–90 mV. [c] One-wave shift in oxidation potential produced by the presence of metal cations added as $NaPF_6$ and KPF_6 salts. Positive values indicate anodic shift, negative values indicate cathodic shift. [d] One-wave shift in oxidation potential produced by a mixture of metal cations added as $NaPF_6$ and KPF_6 salts in equimolar amounts.

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