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FULL PAPER

1,4,8,11-Tetrakis(4-ferrocenyl-3-azabutyl)-1,4,8,11-tetraazacyclotetradecane as a ferrocene-functionalised polyammonium receptor for electrochemical anion sensing

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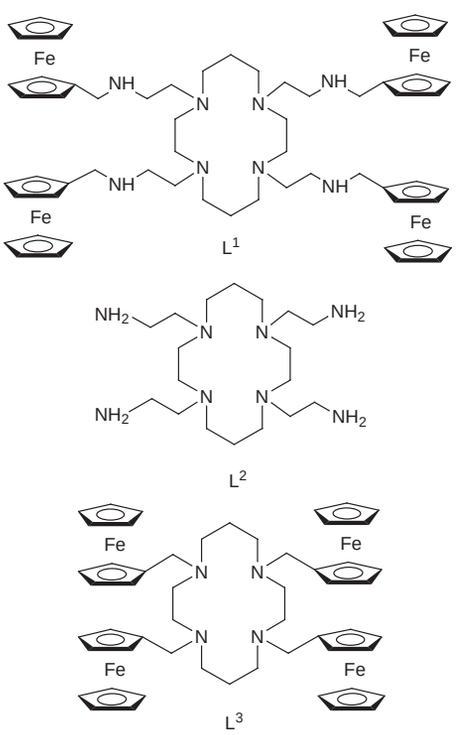
The interaction of the ferrocene-functionalised polyaza receptor 1,4,8,11-tetrakis(4-ferrocenyl-3-azabutyl)-1,4,8,11-tetraazacyclotetradecane (L^1) with sulfate, phosphate and ATP has been studied potentiometrically in THF–water 70 : 30 v/v (0.1 mol dm^{-3} tetrabutylammonium perchlorate, 25 °C). The molecular structure of the free receptor has been determined by single-crystal X-ray procedures. An electrochemical study on L^1 as a function of the pH has been carried out in THF–water 70 : 30 v/v in the presence of the sulfate, phosphate and ATP anions. The potential use of L^1 as an anion sensing receptor is discussed in terms of the electrochemical and potentiometric data and its behaviour is compared with those of related redox-active polyammonium receptors.

Introduction

Redox-active molecular systems have been used as molecular devices for converting molecular recognition processes into macroscopically measurable electronic signals.[1] These redox responsive molecules contain two components: (i) an electroactive group and (ii) binding sites. In many systems it has been reported that the redox properties of the electroactive sites can be affected by substrate binding. As a consequence of this electrochemical shift effect, molecular redox receptors are able to transform chemical information into electronic signals, which can be used for the development of new specific sensors. Although many examples have been reported of the electrochemical sensing of metal ions[2] less effort has been devoted electrochemically to sensing anionic guests especially in aqueous environments.[3] We have recently been involved in the synthesis of ferrocene-functionalised water-soluble receptors specially designed for the electrochemical sensing of toxic heavy metal ions and oxoanions.[4] For anion sensing, the approach followed involves the functionalisation with ferrocenyl groups of polyazaalkanes, which are well known for their ability to form both highly charged species at neutral and basic pH and hydrogen bonding interactions. We have recently reported the synthesis of the highly branched ferrocene polyazacycloalkane receptor 1,4,8,11-tetrakis(4-ferrocenyl-3-azabutyl)-1,4,8,11-tetraazacyclotetradecane (L^1) and studied its utility for cation sensing. Following our interest in the development of molecular receptors able to transform molecular interactions into measurable signals using electrochemical methods, we report here a study of the interaction in THF–water (70 : 30 v/v) of L^1 with the anions sulfate, phosphate and ATP, using potentiometric and electrochemical techniques. The crystal structure of the free receptor is also reported.



Experimental

The synthesis of the receptor L^1 has been published elsewhere.[5] Adenosine 5′-phosphate disodium salt hydrate was purchased from Aldrich.

Physical measurements

Electrochemical data were obtained with a Tacussel IMT-1 programmable function generator, connected to a Tacussel PJT 120-1 potentiostat. The working electrode was graphite with a saturated calomel reference electrode separated from the test solution by a salt bridge containing the solvent/supporting electrolyte. The auxiliary electrode was platinum wire. Potentiometric titrations were carried out in THF–water (70 : 30 v/v, 0.1 mol dm^{-3} tetrabutylammonium perchlorate) using a reaction vessel water-thermostatted at 25.0 ± 0.1 °C under nitrogen. The titrant was added by a Crison microburette 2031. The potentiometric measurements were made using a Crison 2002 pH-meter and a combined glass electrode. The titration system was automatically controlled by a personal computer using a program to monitor the electromotive force values and the volume of titrant added (pH is defined as $-\log[H^+]$). The electrode was dipped in THF–water (70 : 30 v/v) for 0.5 h before use. It was calibrated as a hydrogen concentration probe by titration of known amounts of HCl with CO_2-free KOH solution and determining the equivalence point by Gran's method[6] which gives the standard potential $E°$ and the ionic product of water ($K_w = [H^+][OH^-]$). The computer program SUPERQUAD[7] was used to calculate the protonation and stability constants. The titration curves for each system (*ca.* 250 experimental points corresponding to at least three titration curves, pH range investigated 2.5–10.2, concentration of the ligand and metal ion *ca.* 1.2×10^{-3} mol dm^{-3}) were treated either as a single set or as separate entities without significant variations in the values of the stability constants. Finally the sets of data were merged and treated simultaneously to give the stability constants. Basicity constants: (a) sulfate, log β_1 = 3.28(1); (b) phosphate, log β_1 = 11.85(1), log β_2 = 20.22(2), log β_3 = 24.41(1); (c) ATP, log β_1 = 7.51(1), log β_2 = 11.52(1), log β_3 = 14.07(3).

Structure determination of L^1

Crystal data. $C_{62}H_{84}Fe_4N_8$, M = 1164.8, monoclinic, space group $P2_1/a$, a = 15.148(4), b = 10.778(3), c = 17.919(6) Å, β = 104.25(3)°, Z = 2, U = 2835(2) $Å^3$, D_c = 1.36 g cm^{-3}, λ(Mo-Kα) = 0.71069 Å, T = 296(2) K, μ(Mo-Kα) = 10.48 cm^{-1}.

Measurements were made as previously described[8] using a Rigaku AFC6S diffractometer with graphite monochromated Mo-Kα radiation on a yellow rhomboid crystal of L^1, of dimensions 0.22 × 0.11 × 0.11 mm. A total of 5544 reflections were collected of which 5333 were unique (R_{int} = 0.088). Of these 1344 reflections had $F_o^2 > 3\sigma(F_o^2)$, where $\sigma(F_o^2)$ was estimated from counting statistics.[8,9] Lorentz-polarisation and absorption (ψ scan) corrections were applied. The metal positions were determined from a 3-D Patterson function. This phased the data sufficiently to locate the other atoms from Fourier-difference maps. The structure was refined by full-matrix least-squares analysis on F. Disorder appeared to affect the atoms of the cyclopentadienyl rings and Cp carbons were refined isotropically. Full-matrix least-squares refinement[10] gave unweighted and weighted agreement factors of R = 0.056 and R' = 0.058. Largest peak and hole in the final difference map 0.34, −0.31 e $Å^{-3}$.

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Results and discussion

Crystal structure of L^1

Crystals were obtained as yellow rhomboids from hot acetonitrile solutions of L^1. A similar procedure was used for obtaining high-purity material for potentiometric purposes. A view of the molecule is shown in Fig. 1 and selected bond distances and angles are in Table 1. The structure consists of a 1,4,8,11-tetraazacyclotetradecane (cyclam) framework containing four 4-ferrocenyl-3-azabutyl groups covalently attached to the four nitrogen atoms of the cyclam ring. The compound L^1 has a promising topology for anion binding with a total of eight nitrogen atoms, four of them on a rather rigid macrocycle and the remaining on flexible arms. The ferrocenyl moieties show the typical sandwich conformation; the Cp rings make an angle of 3.0° at Fe(1) but are essentially parallel at Fe(2) (0.8°). The Cp rings are 3.294 Å apart, measured through Fe(1), and 3.289 Å apart measured through Fe(2). There is a crystallographically imposed centre of inversion in the middle of the cyclam ring. Cyclic tetraamines such as [14]aneN_4 or R_4[14]aneN_4 macrocycles can adopt a total of five different conformations due to

Table 1 Selected bond lengths (Å) and angles (°) for L^1

Fe(1)–C(1a)	2.06(1)	Fe(1)–C(2a)	2.03(1)
Fe(1)–C(3a)	2.04(1)	Fe(1)–C(4a)	2.03(1)
Fe(1)–C(5a)	1.99(2)	Fe(1)–C(1b)	2.02(2)
Fe(1)–C(2b)	2.02(1)	Fe(1)–C(3b)	2.01(1)
Fe(1)–C(4b)	2.02(1)	Fe(1)–C(5b)	2.06(2)
Fe(2)–C(1c)	2.06(1)	Fe(2)–C(2c)	2.01(1)
Fe(2)–C(3c)	2.02(1)	Fe(2)–C(4c)	2.00(1)
Fe(2)–C(5c)	2.03(1)	Fe(2)–C(1d)	2.05(1)
Fe(2)–C(2d)	2.04(1)	Fe(2)–C(3d)	2.02(2)
Fe(2)–C(4d)	2.03(1)	Fe(2)–C(5d)	2.01(1)
N(1)–C(1)	1.43(1)	N(1)–C(6a)	1.47(1)
N(2)–C(2)	1.48(1)	N(2)–C(3)	1.48(2)
N(2)–C(2m)	1.42(1)	N(3)–C(5)	1.47(1)
N(3)–C(6)	1.45(2)	N(3)–C(3m)	1.43(2)
N(4)–C(7)	1.47(1)	N(4)–C(6c)	1.46(1)
C(1a)–C(6a)	1.49(2)	C(1)–C(2)	1.54(2)
C(3)–C(4)	1.54(2)	C(4)–C(5)	1.50(2)
C(6)–C(7)	1.50(2)	C(6c)–C(1c)	1.50(2)
C(1)–N(1)–C(6a)	113(1)	C(2)–N(2)–C(3)	110(1)
C(2)–N(2)–C(2m)	114(1)	C(3)–N(2)–C(2m)	109(1)
C(5)–N(3)–C(6)	112(1)	C(5)–N(3)–C(3m)	111(1)
C(6)–N(3)–C(3m)	114(1)	C(7)–N(4)–C(6c)	112(1)
N(1)–C(1)–C(2)	111(1)	N(2)–C(2)–C(1)	111(1)
N(2)–C(3)–C(4)	112(1)	N(3)–C(5)–C(4)	115(1)
N(3)–C(6)–C(7)	115(1)	N(4)–C(7)–C(6)	112(1)
N(2)–C(2m)–C(3m′)	114(1)	N(3)–C(3m)–C(2m′)	118(1)
N(1)–C(6a)–C(1a)	112(1)	N(4)–C(6c)–C(1c)	114(1)

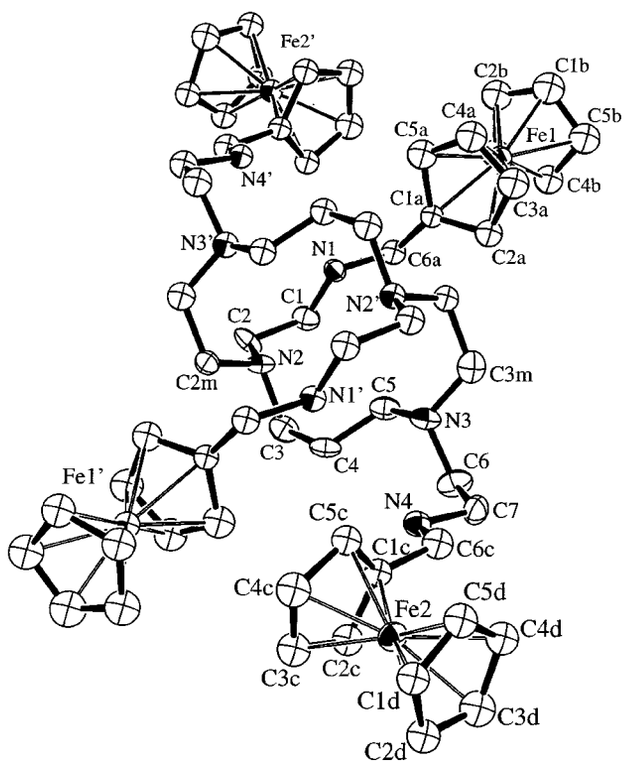

Fig. 1 Molecular structure of the L^1 receptor.

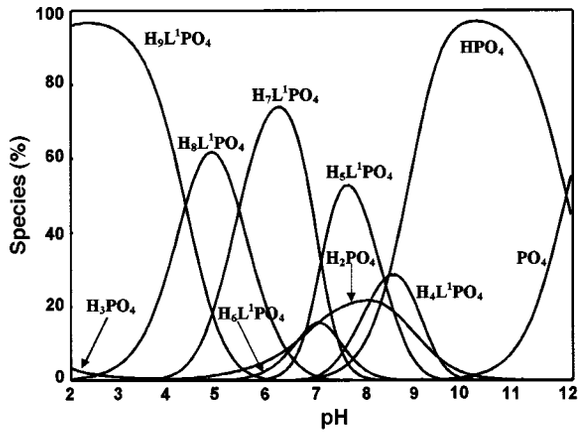

Fig. 2 Distribution diagram of the species for the system L^1–H^+–phosphate.

the presence of four amino groups. Of these, compound L^1 shows a conformation with two 4-ferrocenyl-3-azabutyl groups above the N_4 plane and the two below the N_4 plane. A similar conformation of the cyclam ring was found in the related derivative 1,4,8,11-tetrakis(ferrocenylmethyl)-1,4,8,11-tetraazacyclotetradecane (L^3) also containing four groups attached to the nitrogen atoms. The closest non-hydrogen intermolecular distance is 3.44(2) Å between C(2b) and C(1d) of adjacent molecules. The nearest metal–metal intermolecular distances are 6.014(5) Å between Fe(1) and Fe(2) (symmetry transformation x, y, $z-1$) and 6.271(3) between Fe(1) and Fe(2) (symmetry transformation $\frac{3}{2}-x$, $\frac{1}{2}+y$, $1-z$). The nearest intermolecular metal–metal distance is 6.524(3) Å between Fe(1) and Fe(2′). The other intramolecular distances are 12.570(6) between Fe(1) and Fe(1′), and 17.802(9) Å between Fe(2) and Fe(2′).

Potentiometric anion binding studies

Speciation studies on L^1 have been carried out in THF–water 70:30 v/v (0.1 mol dm^{-3} tetrabutylammonium perchlorate, 25 °C) in the presence of the anions sulfate, phosphate and ATP. Polyamines are known for their ability to form highly charged species at neutral and basic pH and hydrogen-bonding interactions. The protonation behaviour of L^1 has been published elsewhere.[5] The compound contains eight protonation sites and behaves in THF–water 70:30 v/v as an octaprotic base. The high charge achieved by L^1 in solution (at pH 4 the $[H_7L^1]^{7+}$, $[H_6L^1]^{6+}$ and $[H_5L^1]^{5+}$ species coexist) suggests that this compound could be a potential receptor for anions in aqueous environments.

Table 2 gives the stoichiometry of the species found and the stability constants with sulfate, phosphate and ATP. There is interaction between the receptor and phosphate in a wide pH range (from values of *ca.* 10). Fig. 2 shows the distribution diagram of the species for the L^1–H^+–phosphate system. The stability constants corresponding to the equilibrium of L^1 with sulfate have also been determined by pH-metric titrations. The logarithm of the first protonation constant for sulfate in THF–water 70:30 v/v is 3.28. Bearing in mind that the receptor L^1 is fully protonated at pH lower than 1.6, the nature of the complexes expected to exist in solution probably involve the interaction of $[H_jL^1]^{j+}$ species and the SO_4^{2-} anion.

In Table 2 are also given the stability constants of the L^1 polyamine and ATP. The distribution diagram for the species existing in equilibrium in the L^1–H^+–ATP system is shown in Fig. 3. As has been reported in other polyammonium–ATP systems,[11] the strength of the interaction increases with the charge of the complexes formed. This behaviour is also observed for the L^1–H^+–sulfate and L^1–H^+–phosphate systems (see Table 2). However the determination of the nature of the ATP complexes

Table 2 Logarithms of the stability constants for the interaction of L^1 with sulfate, phosphate and ATP in THF–water 70:30 v/v (0.1 mol dm^{-3} tetrabutylammonium perchlorate, 25 °C)

Reaction	Sulfate	Phosphate	ATP
$L + 2H + A \rightleftharpoons H_2LA$ [a]	21.65(5) [b]		21.45(3)
$L + 3H + A \rightleftharpoons H_3LA$	30.04(2)		30.78(3)
$L + 4H + A \rightleftharpoons H_4LA$	37.73(2)	41.39(2)	38.55(3)
$L + 5H + A \rightleftharpoons H_5LA$	44.28(2)	49.63(3)	45.93(3)
$L + 6H + A \rightleftharpoons H_6LA$	49.79(2)	56.30(6)	52.93(2)
$L + 7H + A \rightleftharpoons H_7LA$	54.59(2)	63.60(1)	58.68(2)
$L + 8H + A \rightleftharpoons H_8LA$	57.01(4)	68.95(1)	63.54(2)
$L + 9H + A \rightleftharpoons H_9LA$		73.24(1)	
$H_2L + A \rightleftharpoons H_2LA$	2.99		2.79
$H_3L + A \rightleftharpoons H_3LA$	3.98		4.72
$H_4L + A \rightleftharpoons H_4LA$	4.69	8.35	5.51
$H_5L + A \rightleftharpoons H_5LA$	5.88	11.23	7.53
$H_6L + A \rightleftharpoons H_6LA$	7.30	13.51	10.14
$H_7L + A \rightleftharpoons H_7LA$	8.66	17.67	12.75
$H_8L + A \rightleftharpoons H_8LA$	9.38	21.32	15.91
$H_3L + HA \rightleftharpoons H_4LA$		3.46	
$H_4L + HA \rightleftharpoons H_5LA$		4.72	
$H_5L + HA \rightleftharpoons H_6LA$		6.03	
$H_6L + HA \rightleftharpoons H_7LA$		8.94	
$H_7L + HA \rightleftharpoons H_8LA$		11.15	
$H_8L + HA \rightleftharpoons H_9LA$		13.74	

[a] Charges have been omitted for clarity. [b] Values in parentheses are the standard deviations in the last significant digit.

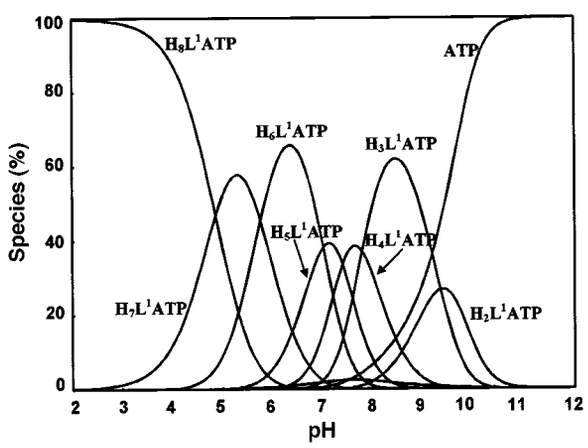

Fig. 3 Distribution diagram of the species for the system L^1–H^+–ATP.

in solution is rather difficult when taking into account stability constant values, because there is a large difference between the first protonation constant for ATP (in THF–water 70:30 v/v log K for $ATP^{4-} + H^+ \rightleftharpoons HATP^{3-}$ is *ca.* 7.5) and the last protonation constant for L^1 (log K for $[H_7L^1]^{7+} + H^+ \rightleftharpoons [H_8L^1]^{8+}$ in THF–water 70:30 v/v is *ca.* 1.6). Both receptor and phosphate can also protonate in a wide pH range and the evaluation of the existing species in solution is not an easy task. The interaction between ATP and the receptor 1,4,8,11-tetra(2-aminoethyl)-1,4,8,11-tetraazacyclotetradecane (L^2) in water has also been reported.[12] Both receptors, L^2 and L^1, are topologically analogous, the only difference between them being the presence in L^1 of four ferrocenylmethyl groups. Nevertheless stability constants found in THF–water 70:30 v/v for the L^1–H^+–ATP system are higher than those found for L^2 and ATP in water. In the case of the L^2–ATP system the constants range from log $K = 1.7$ for $[H_3L^2]^{3+} + ATP^{4-} \rightleftharpoons [L^2H_3ATP]^-$ to 5.71 for $[H_6L^2]^{6+} + ATP^{4-} \rightleftharpoons [L^2H_6ATP]^{2+}$. In our case the stability constants for the analogous equilibria are log $K = 4.72$ for $[H_3L^1]^{3+} + ATP^{4-} \rightleftharpoons [L^1H_3ATP]^-$ and 10.14 for $[H_6L^1]^{6+} + ATP^{4-} \rightleftharpoons [L^1H_6ATP]^{2+}$. This different affinity between L^2 and L^1 for ATP may be explained by taking into account that a reduction of the relative permittivity occurs in THF–water when compared with

water; therefore there is an enhancement, in THF–water, of the electrostatic interaction between anion and cation species. This appears to be also suggested by the relatively high stability constants found for the L^1–H^+–sulfate and L^1–H^+–phosphate systems. However the presence of secondary nitrogen atoms in L^1 instead of primary ones (as in L^2) could also have some influence in explaining the different affinity of L^2 and L^1 towards ATP.

One of our main goals is to find electroactive receptors which may display a selective electrochemical response against a target anion in the presence of competing guests. Speciation studies are of importance for correlating the electrochemical response (see below) and the existing species in solution at certain pH values. However to deduce the nature of the complexes in a mixture of the receptor and two or more competing anions is rather difficult given that one or more protons can be bound to the anions (this is especially so for phosphate and ATP) and to the polyammonium receptor. It has been suggested that a way to avoid these problems is to plot diagrams of the ternary systems L–H^+–anion 1–anion 2 containing the receptor L and a couple of anions.[13] The calculation of the overall percentages of each anion bound to the receptor over a determined pH range allows us to plot percentage *versus* pH distribution diagrams which give information about the relative selectivity of receptor L against the two anions. Ternary L^1–H^+–ATP–sulfate and L^1–H^+–ATP–phosphate diagrams reveal the ability of L^1 in binding ATP over sulfate or phosphate, whereas ternary L^1–H^+–sulfate–phosphate shows the greater affinity of L^1 for sulfate in the pH range studied (see Fig. 4). We have also recently studied the interaction between the receptor L^3 and sulfate, phosphate and ATP.[14] In this case the ternary diagrams showed that L^3 has a greater affinity for ATP over sulfate over the entire pH range studied (see Fig. 5). Compound L^3 also shows a greater ability to bind ATP over phosphate except at basic and very acid pH values. Finally L^3–H^+–sulfate-phosphate ternary diagrams show a greater binding ability of L^3 for sulfate over phosphate at acidic pH and for phosphate over sulfate at basic pH. Whereas ATP forms the most stable complexes with both L^1 and L^3 receptors, there is a substantial change in selectivity for the sulfate–phosphate couple. The different molecular architecture, the number of N donor atoms and their different basicity are among the factors which could account for the different selective binding behaviour observed for L^1 and L^3. Further studies are being undertaken to find selective behaviour in redox-functionalised polyammonium receptors against sulfate–phosphate or phosphate–ATP competing anions.

Electrochemical anion recognition

One of the most interesting aspects of redox-functionalised receptors is their ability to transform molecular information into a macroscopic electrochemical response. This can be achieved mainly due to the presence of electroactive ferrocene groups near binding sites. The electroactive ferrocene group acts as an amplifier of chemical information. Such amplification is selective in some cases, given that only target species are able to modify the oxidation potential of the ferrocene group at certain pH values. The shift of the redox potential of the ferrocenyl groups as a function of the pH in the absence and presence of sulfate, phosphate and ATP was monitored in THF–water 70 : 30 v/v (0.1 mol dm^{-3} tetrabutylammonium perchlorate, 25 °C). The electrochemical characterisation of the free receptor has been published elsewhere.[5] Receptor L^1 shows well defined four-electron waves over all the pH range studied. The difference between the half-wave oxidation potential at basic pH (pH *ca.* 10, $E_{\frac{1}{2}}$ = 389 mV *vs.* SCE) and acid (pH *ca.* 3, $E_{\frac{1}{2}}$ = 482 mV *vs.* SCE) is 93 mV. As observed in related systems there is a steady anodic shift of the redox potential from basic to acidic pH.

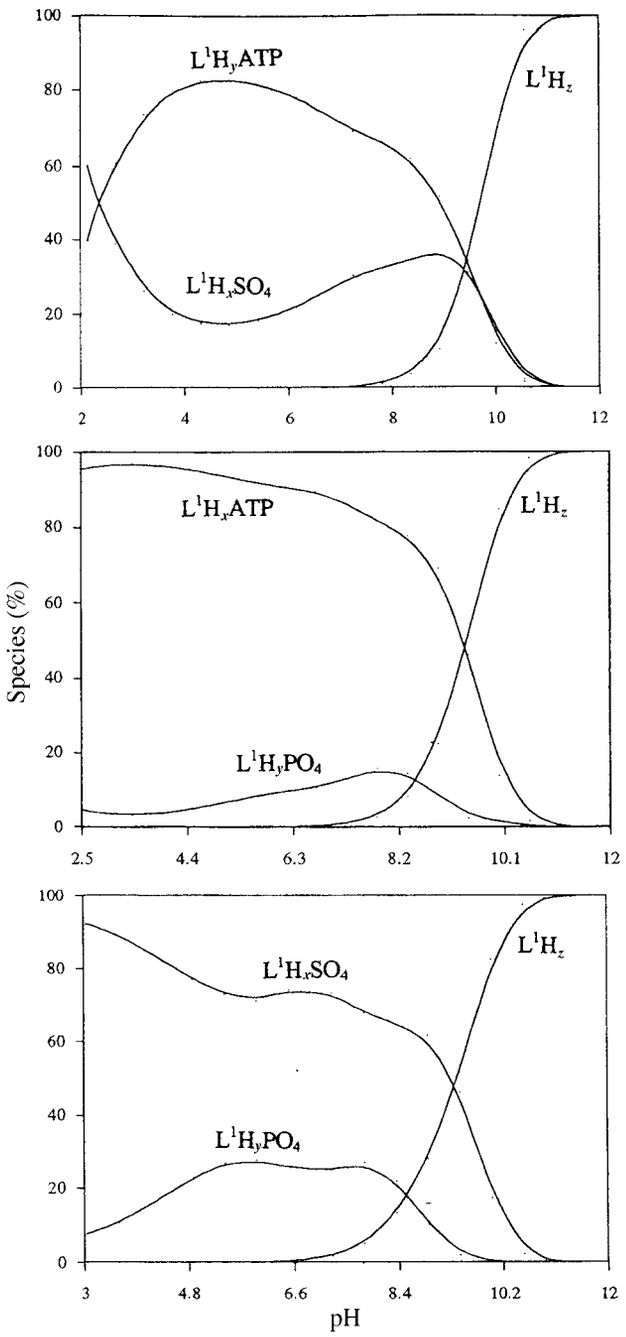

Fig. 4 Distribution diagram for the ternary systems L^1–H^+–ATP–sulfate, L^1–H^+–ATP–phosphate and L^1–H^+–phosphate–sulfate. The sum of percentages of complexed species are plotted *vs.* pH.

Plots of $E_{\frac{1}{2}}$ *versus* pH for L^1–H^+–A (A = sulfate, phosphate or ATP) systems with ligand-to-anion molar ratios = 1 : 1 are displayed in Fig. 6 [$\Delta E_{\frac{1}{2}}$ is defined in the figure as $E_{\frac{1}{2}}$(receptor) − $E_{\frac{1}{2}}$(anion receptor)]. All anions produce maximum cathodic shifts of the redox potential of the ferrocenyl groups at acidic pH, whereas the perturbation of the redox potential is steadily reduced when the pH increases. If we compare the potentiometric data and the electrochemical response as a function of the pH some conclusions can be drawn. Receptor L^1 forms stable complexes with sulfate, phosphate and ATP over a wide pH range (from values of *ca.* 10, see above). However the various species found in solution show a different contribution to the shift of the redox potential ($\Delta E_{\frac{1}{2}}$). For instance, in the L^1–H^+–sulfate system, sulfate interacts with L^1 from pH values of *ca.* 11, but only at pH lower than 6 was an electrochemical response observed. This indicates that only the $[L^1H_7SO_4]^{5+}$ and $[L^1H_8SO_4]^{6+}$ species produce a significant perturbation of the

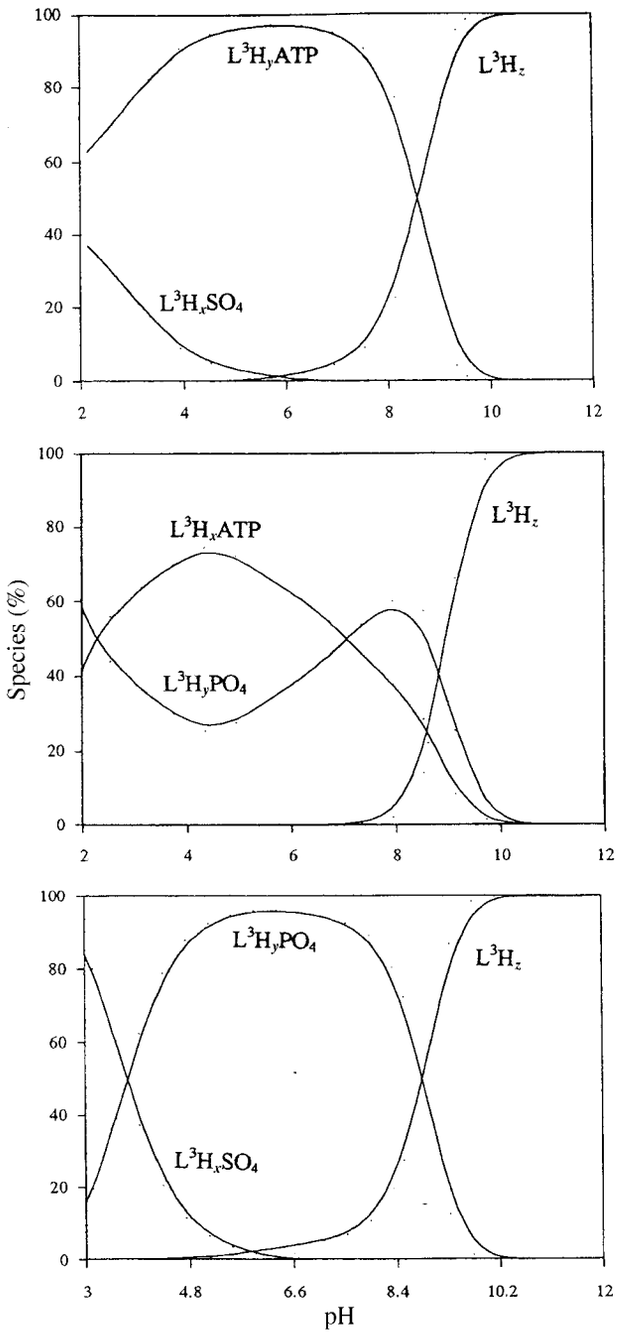

Fig. 5 Distribution diagram for the ternary systems L^3–H^+–ATP–sulfate, L^3–H^+–ATP–phosphate and L^3–H^+–phosphate–sulfate. The sum of percentages of complexed species are plotted *vs.* pH.

redox potential of the ferrocenyl groups, whereas $[L^1H_6SO_4]^{4+}$, $[L^1H_5SO_4]^{3+}$, $[L^1H_4SO_4]^{2+}$, $[L^1H_3SO_4]^{+}$ and $[L^1H_2SO_4]$ do not produce any significant redox potential shift. Similar behaviour can be observed for the L^1–H^+–phosphate and L^1–H^+–ATP systems for which a maximum electrochemical response was found for the species existing at pH lower than *ca.* 6. As we have recently pointed out [14] this suggests that there is a selective electrochemical speciation process, bearing in mind that different anionic species (for instance PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^{-}$, ATP^{4-}, $HATP^{3-}$, H_2ATP^{2-}, H_3ATP^{-}, *etc.*) produce a different redox potential shift.

We have recently reported that some redox-active ferrocene polyazamacrocycles can selectively detect sulfate and phosphate at certain pH values in the presence of competing anions in the aqueous environment.[14] This is of some importance since the development of oxoanion sensing receptors is of considerable interest in fields such as environmental and biological

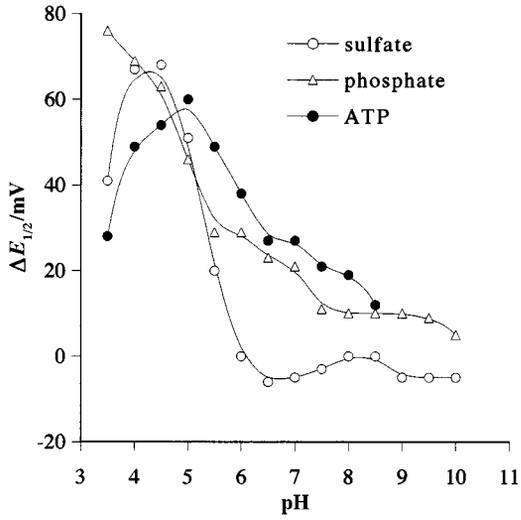

Fig. 6 Redox potential shift ($\Delta E_{\frac{1}{2}}$) for L^1 in the presence of phosphate, sulfate and ATP as a function of the pH.

chemistry. In our case the electrochemical experiments suggest that there is a selective electrochemical response against phosphate over sulfate at the environmentally common pH 6–7 (see Fig. 6), because phosphate produces a cathodic oxidation potential shift of *ca.* 25 mV whereas sulfate is essentially unable to modify the oxidation potential of the ferrocenyl groups at this pH. However these electrochemical experiments are not adequate to predict the electrochemical response in a mixture of anions and L^1. This information can be obtained using ternary diagrams from potentiometric measurements. As noted above, L^1–H^+–phosphate–sulfate diagrams indicate a greater ability of L^1 in binding sulfate than phosphate in an equimolecular mixture of these anions and therefore, although electrochemical techniques suggested a potential selective electrochemical sensing of phosphate in the presence of sulfate, potentiometric measurements indicate that in the presence of the competing anion sulfate that would not be possible.

It is also noteworthy to compare the electrochemical response of receptor L^1 against anions and metal ions. The electrochemical response of L^1 against Cu^{2+}, Zn^{2+} and Cd^{2+} has recently been reported.[5] The maximum shift in oxidation potential of the ferrocenyl groups was around 20 mV (cathodically for Cu^{2+} at pH 4 and anodically for Cu^{2+}, Zn^{2+} and Cd^{2+} at pH 9). This low electrochemical shift contrasts with that found for sulfate, phosphate and ATP which is up to *ca.* 70 mV (see Fig. 6).

We have also recently reported an electrochemical study of the related redox-functionalised cyclic tetraamine L^3 with the anions sulfate, phosphate and ATP.[14] The shift of the oxidation potential of the ferrocenyl groups was lower in this case than that found for receptor L^1. With L^3, ATP produces a maximum cathodic shift, at pH *ca.* 3–4, of 35 mV; $\Delta E_{\frac{1}{2}}$ for sulfate was near 17 mV at pH *ca.* 5, whereas phosphate produces oxidation potential shifts lower than 5 mV over the entire pH range studied. The presence of 4-ferrocenyl-3-azabutyl groups in L^1 instead of the ferrocenylmethyl groups of L^3, attached to the cyclam framework, introduces an enhancement of the oxidation potential shift (maximum $\Delta E_{\frac{1}{2}}$ values *ca.* 80 mV) pointing out the importance of the molecular architecture (different topological distribution and number of redox-active groups) in the electrochemical sensing of anions.

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