ELSEVIER

Coordination Chemistry Reviews
205 (2000) 131–155

COORDINATION CHEMISTRY REVIEWS

www.elsevier.com/locate/ccr

Electrochemical and optical sensing of anions by transition metal based receptors

Paul D. Beer *, James Cadman

Department of Chemistry, Inorganic Chemistry Laboratory, University of Oxford, South Parks Road, Oxford, OX1 3QR, UK

Received 21 May 1999; accepted 31 December 1999

Contents

Abstract

This review focuses on the electrochemical and optical sensing of anionic guest species in organic and aqueous media using transition metal signalling units such as cobaltocenium, ferrocene and ruthenium (II) bipyridyl incorporated into various acyclic, macrocyclic and calix[4]arene ligand frameworks.

Keywords: Electrochemistry; Fluorescence; Sensing anions

1. Introduction

Anions are ubiquitous in numerous biological and chemical processes and their importance in medicine and the environment is now being realised [1]. For example, cystic fibrosis is known to be caused by a misregulation of chloride channels [2] and Alzheimer's has been linked to anion-binding enzymes [3].

---

* Corresponding author. Tel.: +44-1865-272632; fax: +44-1865-272690.
E-mail address: paul.beer@chem.ox.ac.uk (P.D. Beer).

0010-8545/00/$ - see front matter
PII: S0010-8545(00)00237-X

In addition, pollutants such as nitrate and phosphate from soil water, [4] and radioactive pertechnetate [5] from the nuclear fuel cycle need to be extracted and/or continually monitored.

Since the beginning of anion co-ordination chemistry in the late 1960s [6] the main strategies in the design of synthetic anion complexing reagents have focused on cationic polyammonium, guanidinium, quaternary ammonium, expanded porphyrin host systems and a variety of Lewis acidic containing receptors such as tin, boron, silicon, mercury and uranyl. Neutral organic receptors which bind anions solely via favourable hydrogen bond interactions have also been recently exploited. Recent reviews on the general field of anion co-ordination chemistry can be found in the references [7–11].

The design of receptors that have the ability to selectively bind and sense the anion recognition event via a macroscopic physical response is the subject of this review. We have initiated a research programme aimed at the construction of innovative electrochemical and spectral sensory reagents for anions based on novel transition metal organometallic and co-ordination receptor systems. Incorporating these signalling probes into various acyclic, macrocyclic and calixarene ligand frameworks leads to new receptor systems capable of responding to anion complexation. This article reviews our current progress in this area.

2. Electrochemical recognition of anions

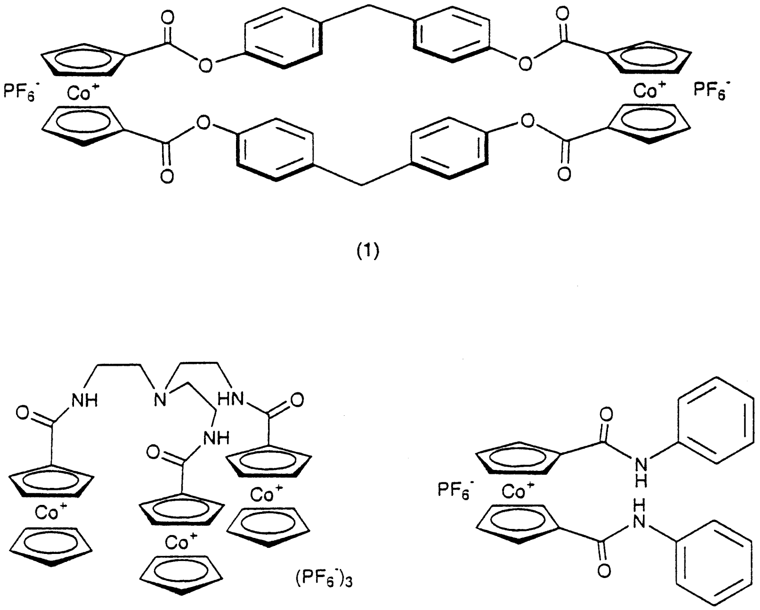
A variety of organic, organometallic and inorganic redox active centres have been successfully incorporated into various host frameworks and shown to electrochemically detect charged and neutral guest species [12,46].

Of the inorganic redox-active centres used, the most prevalent have been the metallocene moieties cobaltocenium and ferrocene.

2.1. Cobaltocenium-based anion receptors

The first redox-responsive class of anion receptor based on the cobaltocenium moiety was reported by Beer and co-workers in 1989 [13]. The macrocyclic ester-linked receptor **(1)** bound and electrochemically sensed bromide via favourable electrostatic interactions. Appending hydrogen bond donor amide groups to the redox centre gave a variety of amide acyclic cobaltocenium receptors [14] (Fig. 1).

Proton NMR titration experiments conducted in DMSO-d_6 showed that through significant amide and cyclopentadienyl proton perturbations receptors **(2)** and **(3)** bound dihydrogenphosphate selectively over chloride. Complex stability constants were calculated [15] for dihydrogenphosphate to be 1200 and 320 M^{-1} for (**2**) and (**3**), respectively, which is approximately an order of magnitude increase in binding on going from chloride to dihydrogenphosphate. This could be attributed to the greater hydrogen bond donating and accepting ability of this anion.



(1)

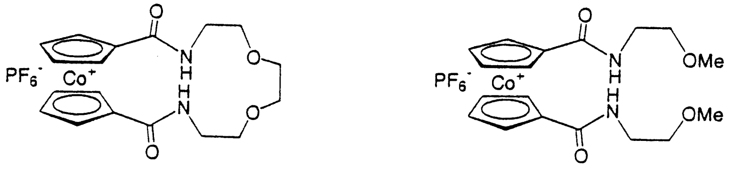
(2)

(3)

Fig. 1. An ester-linked receptor and two amide cobaltocenium-based receptors for anions.

Cyclic voltammetric experiments demonstrated that these molecules can electrochemically sense anions. The addition of anions to acetonitrile solutions resulted in significant cathodic shifts of the reversible Cp_2Co^+/Cp_2Co redox couple. The complexed anionic guest stabilises the positive cobalt centre and thus it is harder to reduce. This means that in the presence of an anion the reducing potential of the couple in question will be greater, i.e. more negative.

For compounds **(2)** and **(3)**, respectively, chloride produced cathodic shifts of 30 and 85 mV, and with dihydrogenphosphate larger magnitudes 200 and 240 mV were observed. This result complements the stability constant data in which the highest K values were obtained with the $H_2PO_4^-$ anion. The importance of the amide moiety hydrogen bonding to anions was highlighted when tertiary amide cobaltocenium analogues were shown not to electrochemically respond to anions.



(4)

(5)

Fig. 2. Two cobaltocenium receptors, the macrocycle and acycle analogues.

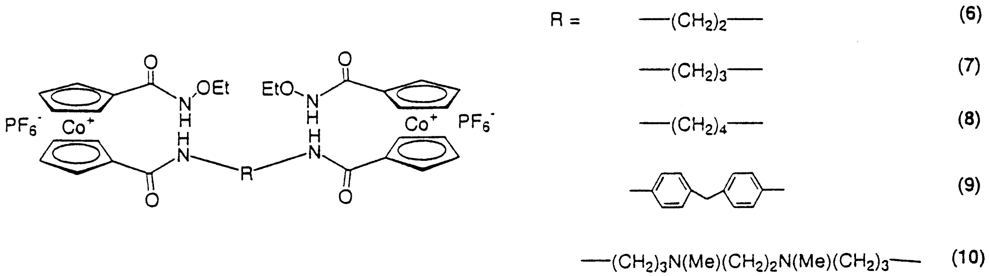


Fig. 3. The cleft type ditopic receptor.

Evidence for an anionic 'macrocyclic effect' was obtained with the two compounds in Fig. 2. Proton NMR titrations with chloride in deuterated DMSO gave stability constants of 250 M^{-1} for the macrocycle **(4)** and 20 M^{-1} for its acyclic analogue **(5)**, an enhancement of over ten-fold.

The next generation of cobaltocenium receptors were ditopic in nature, where two cobaltocenium units are separated by different alkyl and aryl moieties (Fig. 3) [15].

It was found that receptors **(6)**, **(7)** and **(8)** preferred chloride over bromide and iodide in their 1:1 complexes, but on increasing the alkyl chain spacer length the general trend was for lower stability constants for all halides and concomitant decreasing selectivity for chloride (Table 1).

The host molecules containing longer alkyl amino and aryl spacers **(9)** and **(10)** produced 2:1 complexes of anion to receptor, presumably due to the greater size of the cleft's cavity.

Electrochemical experiments endorsed the NMR data with a variety of anions causing significant cathodic shifts in the redox wave of the cobaltocenium centre, dihydrogenphosphate, again producing the largest perturbation of 250 mV.

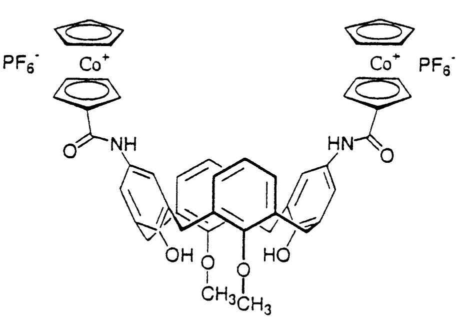
With the aim of creating unique topologies at the anion binding site a variety of novel calixarene receptors **(11)–(14)** have been prepared [16,47] (Fig. 4).

The ^{1}H NMR data shown in Table 2 indicate stronger binding of chloride over dihydrogenphosphate for **(11)**, the opposite trend found for compounds **(2)** and **(3)**, which is quite rare.

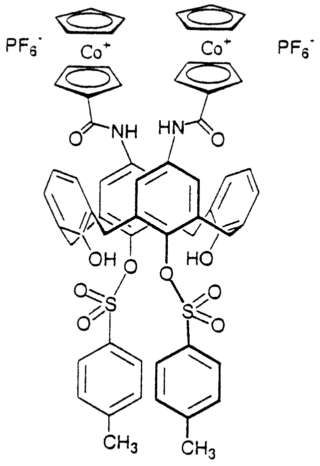
Table 1
Stability constants for receptors **(6)**, **(7)** and **(8)** conducted in acetonitrile-d_3[a]

Receptor	K (dm^3 mol^{-1})		
	Cl^-	Br^-	I^-
(6)	2500	330	450
(7)	1300	270	275
(8)	280	260	100

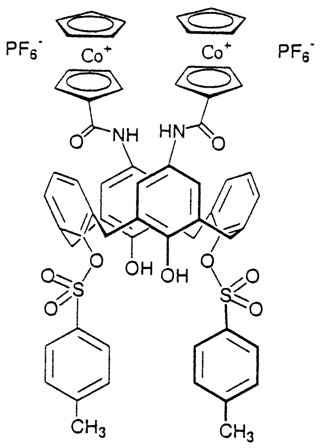
[a] Errors estimated to be ≤10%.



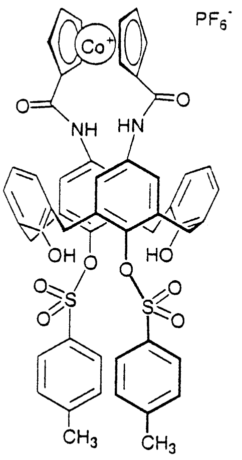
(11)



(12)



(13)



(14)

Fig. 4. Cobaltocenium calix[4]arene receptors.

However, the seemingly subtle alteration of the nature of the anion binding site with respect to the lower rim functionalities can play a major rôle in the overall anion guest preference of the receptor. This can be seen by comparing the stability constants for receptors **(11)**, **(12)** and **(13)**. Compounds **(12)** and **(13)** are regioisomers and the position of the lower rim substituents dictates the anion selectivity properties of the receptor. In **(12)** the tosyl groups are para to the cobaltocenium

Table 2
Stability constants for receptors **(11)**, **(12)**, **(13)**

Solvent	DMSO-d_6		
Anions	Cl^-	Br^-	$H_2PO_4^-$
(11)	5035	1680	2800
(12)	10	–	3100
(13)	400	–	2500

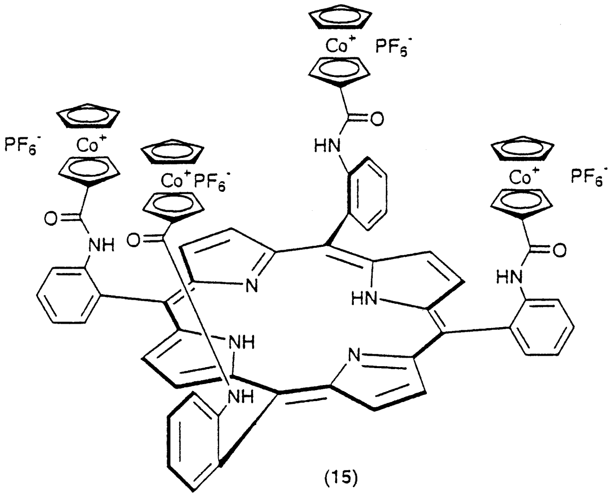
amide moieties. This results in strong binding of dihydrogenphosphate and negligible binding of chloride. However in isomeric **(13)** the *K* value for dihydrogenphosphate significantly decreases and that of chloride increases. This is ascribed to the bulky tosyl groups in **(12)** forcing the cobaltocenium groups together, favouring dihydrogenphosphate over chloride binding, whereas in **(13)** the cobaltocenium groups can move apart and this favours chloride binding. The comparison of changing the chemical nature of substituents rather than position can be realised in **(11)** and **(13)**. The bulky lower rim tosyl group is replaced in **(11)** with smaller methyls. This allows far better binding of chloride, to the extent of it being selective over dihydrogenphosphate.

The preorganised upper rim bridged cobaltocenium calix[4]arene receptor **(14)** is selective for carboxylate anions (Fig. 4). Proton NMR titrations in DMSO revealed **(14)** binds halides, nitrate and hydrogensulphate weakly, stability constant values in the region of 100 M^{-1}, and binds carboxylates with very high values such as acetate $K = 41\ 520\ M^{-1}$. Similar values were recorded for benzoate, phenylacetate and β-naphthylcarboxylate. Such selectivity was attributed to the cobaltocenium bridging unit creating an ideal bidentate amide hydrogen bond donor environment of complementary topology for recognising the bidentate carboxylate anion. Electrochemical anion titrations showed carboxylate anions caused large cathodic shifts of $\Delta E \geq 140$ mV of the cobaltocenium redox couple of **(14)**.

Porphyrins have a well-established redox and photoactive behaviour [17] but cannot bind anions themselves at physiological pH due to their neutrality. However, when appended with cobaltocenium moieties the framework becomes a receptor for anions [18] (Fig. 5).

Evidence for anion binding with **(15)** came initially from ^{1}H NMR titrations in acetonitrile. The amide, cyclopentadienyl and pyrrole protons all shifted downfield by up to 0.7ppm giving titration curves that showed 1:1 binding stoichiometry and stability constants of 860 M^{-1} and 820 M^{-1} for chloride and bromide were calculated. In contrast **(15)** forms a weaker complex with nitrate $K = 190\ M^{-1}$.

Cyclic and square-wave voltammetric studies on the free ligand gave the usual pattern for a ‘picket-fence’ atropisomer; a two-electron oxidation of the porphyrin at $+0.75$ V, two one-electron reductions of the porphyrin at -1.24 and -1.60 V superimposed on which was the four electron reduction of the cobaltocenium moieties at -1.50 V.



(15)

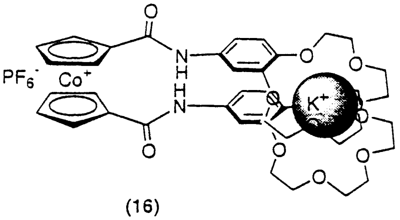
Fig. 5. Novel cobaltocenium porphyrin receptor.

When compound **(15)** was titrated in acetonitrile with the TBA-salts of chloride, bromide, hydrogensulphate and dihydrogenphosphate, cathodic shifts of 40, 35, 75 and 225 mV of the cobaltocenium redox couple were noted. Nitrate on the other hand produced no significant perturbation in the redox potentials. The porphyrin oxidation couple also witnessed cathodic shifts of lesser magnitudes.

The cobaltocenium-crown-ether ligand **(16)** exhibits switchable anion binding effects induced by potassium cations [19]. Proton NMR experiments with halides in acetonitrile gave log K_{stab}'s of 3.1 for chloride and 3.0 for bromide.

Analogous anion titrations in the presence of K^+ revealed, however, no significant amide proton downfield shifts. This was rationalised by K^+ forming a sandwich complex between the two crown ethers bringing the two amide binding functionalities close together and making them less accessible for anion binding (Fig. 6).

These results were borne out in electrochemical studies. The receptor's redox couple shifted cathodically by 60 and 30 mV on addition of chloride and bromide anions respectively. However in the presence of K^+ no electrochemical recognition of halide was observed.



(16)

Fig. 6. Cobaltocenium crown-ether receptors.

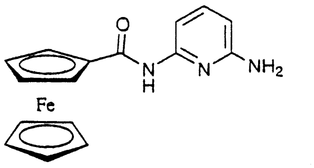
2.2. Ferrocene-based anion receptors

The ferrocene moiety has also been exploited in the electrochemical sensing of anions.

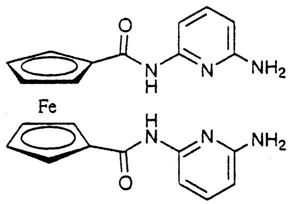
Many ferrocene-based host molecules have been created incorporating amide and amine functionalities starting from acid chloride and aldehyde precursor derivatives, respectively [20,21].

2.2.1. Ferrocene-based receptors for electrochemically sensing anions in organic solvents

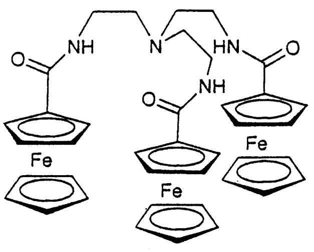
Ferrocene units appended with secondary amides have been used for anion recognition **(17)–(21)** (Fig. 7) [22]. Being neutral these receptors have no inherent electrostatic attraction making the NMR determined stability constants lower in magnitude than for the analogous cobaltocenium systems. Electrostatic interactions



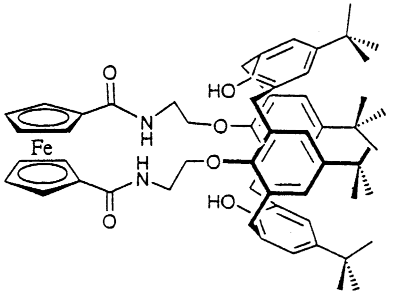
(17)



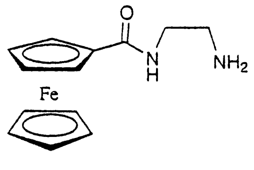
(18)



(19)

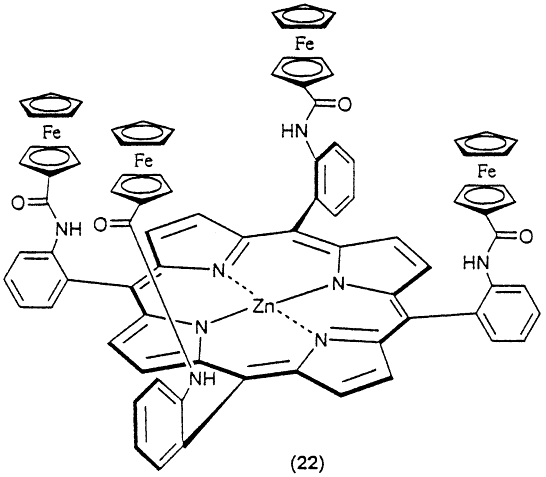


(20)



(21)

Fig. 7. Ferrocene-amide based receptors.

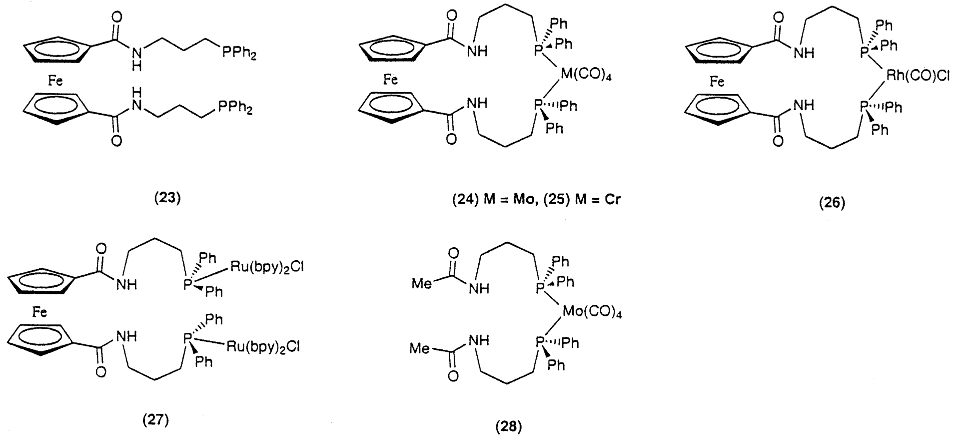


(22)

Fig. 8. The α,α,α,α-ferrocene-amide-porphyrin receptor.

can, however, be switched on by oxidation of ferrocene to ferrocenium and consequently these molecules exhibit interesting electrochemical anion recognition effects. For example **(17)–(20)** were capable of detecting $H_2PO_4^-$ anions via large cathodic shifts of up to 240 mV in the presence of a ten-fold excess of HSO_4^- and Cl^- ions. In contrast receptor **(21)** binds HSO_4^- selectively in the presence of $H_2PO_4^-$. The basic amine functionality of **(21)** is protonated by the acidic hydrogen sulfate anion and the positively charged receptor strongly binds the produced SO_4^{2-} as noted by a marked electrochemical reductive stripping response.

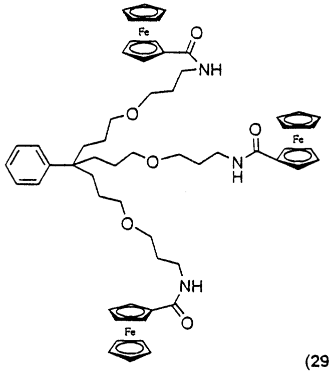
Ferrocene-zinc metalloporphyrin receptors **(22)** (Fig. 8) have been prepared and shown to bind anions via the Lewis acidic zinc centre and favourable amide hydrogen bonding effects [23]. The particular atropisomer dictates the anion



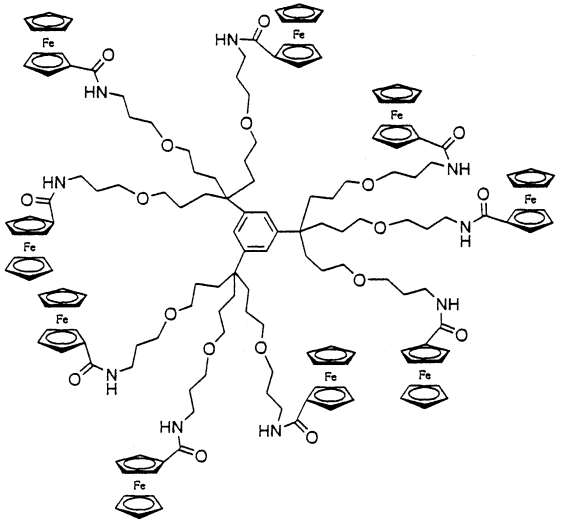
(23) **(24) M = Mo, (25) M = Cr** **(26)**

(27) **(28)**

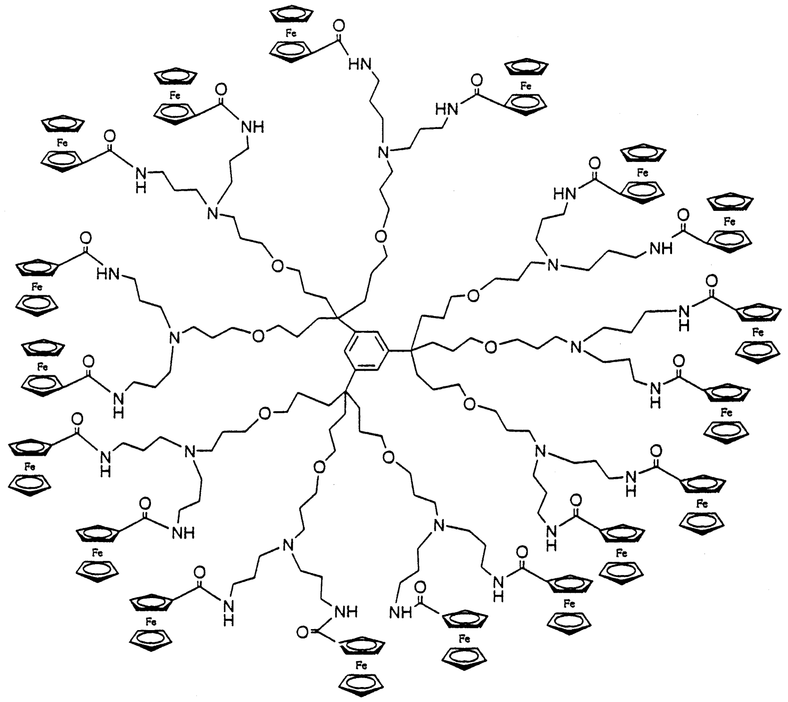
Fig. 9. Ferrocene-amide transition metal receptors.



(29)



(30)



(31)

Fig. 10. Astruc's ferrocene dendrimers.

Table 3
The ^{1}H NMR stability constant data for **(22)** and its atropisomers in CD_2Cl_2

Receptor	Anion	K (dm^3 mol^{-1})*
α,α,α,α **(22)**	Br^-	6200
	NO_3^-	2300
	HSO_4^-	2100
α,α,α,β	Cl^-	3200
	NO_3^-	5000
	HSO_4^-	2000
α,α,β,β	Cl^-	5600
	Br^-	1600
	NO_3^-	900
	HSO_4^-	1000
α,β,α,β	Br^-	5800
	NO_3^-	1300
	HSO_4^-	600

* Errors ≤ 10%.

selectivity preference displayed (Table 3). Electrochemical studies revealed anion induced cathodic shifts of the porphyrin centred oxidation and ferrocene redox couples (Table 4).

Neutral and charged transition metal coordinated ferrocene phosphine amide receptors **(23)–(28)** (Fig. 9) bind and sense anions in dichloromethane/acetonitrile solvent mixtures [24]. A comparison of stability constant values suggests the combination of the transition metal and ferrocene amide moiety enhances the

Table 4
Cathodic shifts of the porphyrin oxidation and the ferrocene redox couples on addition of anions[a]

Receptor	Oxidation	ΔE (mV)			
		Cl^-	Br^-	NO_3^-	HSO_4^-
α,α,α,α **(22)**	Pph	115	85	110	100
	Fc	30	20	25	60
α,α,α,β	Pph	90	75	100	125
	Fc[b]	25	20	20	50
α,α,β,β	Pph	95	80	75	175
	Fc	25	25	20	110
α,β,α,β	Pph	70	65	60	150
	Fc	20	20	15	105

[a] Conducted in 3:2 CH_2Cl_2-CH_3CN solution with 0.2M NBu_4BF_4 as supporting electrolyte. Receptors were ca. 5×10^{-4} M and potentials were determined versus a Ag^+/Ag reference electrode. Cathodic shifts induced by up to five equivalents of anion as the TBA salt.

[b] Average shift of the two waves.

strength of anion binding (Table 5). All receptors electrochemically recognised anions via significant cathodic perturbations of the respective ferrocene and transition metal oxidation wave (Table 6).

Astruc and co-workers have produced dendrimers containing three **(29)**, nine **(30)** and eighteen **(31)** ferrocene units (Fig. 10) and found evidence for a dendritic effect in the anion recognition process [25]. The electrochemical data for **(29)–(31)** is shown in Table 7. The largest anion induced cathodic shift is observed on addition of $H_2PO_4^-$ however as the size of the dendrimer increases so does the perturbation caused by a particular anion.

Lower rim poly-ferrocene substituted calixarenes [26] (Fig. 11) have been recently shown to bind and electrochemically sense anions with maximum perturbations of 160 mV being observed with $H_2PO_4^-$.

2.2.2. Ferrocene-based receptors for electrochemically sensing anions in aqueous media

Designing receptors that can bind and sense anions in water is a challenge as anion hydration energies are large [8].

Beer and co-workers synthesised several ferrocene-amine receptors, which were shown to bind and electrochemically sense transition metal cations and phosphate anions in water [20,27].

Receptors **(32)**, **(33)** and **(34)** (Fig. 12) were initially shown to bind adenosine triphosphate (ATP) and hydrogenphosphate using ^{31}P NMR in water. These experiments showed that at pH = 6.5 1:1 complexes were formed, where at least two of the nitrogen atoms are protonated.

Cyclic voltammetric experiments revealed the receptors to sense these phosphate anions at pH 6.5 via cathodic shifts of 60–80 mV.

In more recent years a series of acyclic and macrocyclic ferrocene amine ligands have been synthesised and studied for the selective binding properties of phosphate and sulphate in aqueous media [28].

Table 5
^1H NMR-derived stability constants for the ferrocene-phosphine receptors[a]

	K_{stab} (dm^3 mol^{-1b} Cl^-)	K_{stab} (dm^3 mol^{-1b} Br^-)	K_{stab} (dm^3 mol^{-1b} I^-)	K_{stab} (dm^3 mol^{-1b} $H_2PO_4^-$)
(23)	10	–	–	10
(24)	70	50	10	20
(25)	70	60	15	20
(26)	20	nb	nb	nb
(27)	240	320	250	ppt
(28)	70	40	20	50

[a] EQNMR analysis of titration curve of particular receptor proton, conducted in CD_2Cl_2 at 25°C.

[b] Errors estimated ≤20%; nb, no binding; ppt, precipitate.

Table 6
The cathodic shifts of the phosphine receptors on anion addition

	ΔE_{pa} (mv)						
	Cl^{-a}		Br^{-a}		HSO_4^{-a}		$H_2PO_4^{-a}$
	Fc^+/Fc	M	Fc^+/Fc	M	Fc^+/Fc	M	Fc^+/Fc
(23)	65	–	30	–	70	–	135
(24)	90	95	30	30	35	50	135
(25)	85	30	30	55	35	30	185
(26)	65	80	–	–	60	30	–
(27)	70	25	35	–	45	45	180
(28)	–	25	–	25	–	25	–

[a] Conducted in 1:1 CH_3CN/CH_2Cl_2 with Bu_4NPF_6 as supporting electrolyte and a Ag^+/Ag reference electrode, cathodic shifts after five equivalents anion as TBA^+X^-.

It was found that, at different pH values, different ligands were capable of the selective electrochemical detection for either phosphate over sulphate, or vice-versa (Fig. 12).

For receptor **(35)** using 70:30 THF/H_2O the results showed that it was electrochemically discriminating for sulphate over phosphate at pH4 with a cathodic shift of 54 mV, whereas phosphate induced < 10 mV change. Likewise compound **(36)** perturbed the Fc^+/Fc couple with sulphate by 23 mV at pH 4 and by 30 mV for phosphate at pH 8.

For **(33)** the experiments were conducted in water (0.1 M KNO_3 used as supporting electrolyte). Here it turned out that phosphate perturbed the redox wave by 50 mV at pH 7 but sulphate on the other hand barely altered the redox response (Fig. 13).

Calibration curves of the change in the half-wave potential versus the anion-to-ligand ratio ($\Delta E_{\frac{1}{2}}$ vs. $[A^-]/[L]$) were drawn up at the pH where one anion was preferred over the other. From these curves the concentration of anion could be calculated from the perturbation of the redox wave of the ferrocene receptor, $\Delta E_{\frac{1}{2}}$, with varying guest concentrations. This was undertaken in the presence of competing anions (Fig. 14).

Table 7
Titration of the ferrocene dendrimers **(29)–(31)** by various n-$Bu_4N^+X^-$ salts monitored by the variation ΔE (mV for one equivalent of anion per branch) of the standard redox potential of the redox couple in CV in dichloromethane versus SCE

	(29)(3-Fc)	**(30)**(9-Fc)	**(31)**(18-Fc)
$H_2PO_4^-$	110	220	315
HSO_4^-	30	65	130
Cl^-	<20 mV	20	45
NO_3^-	<20 mV	<20 mV	30

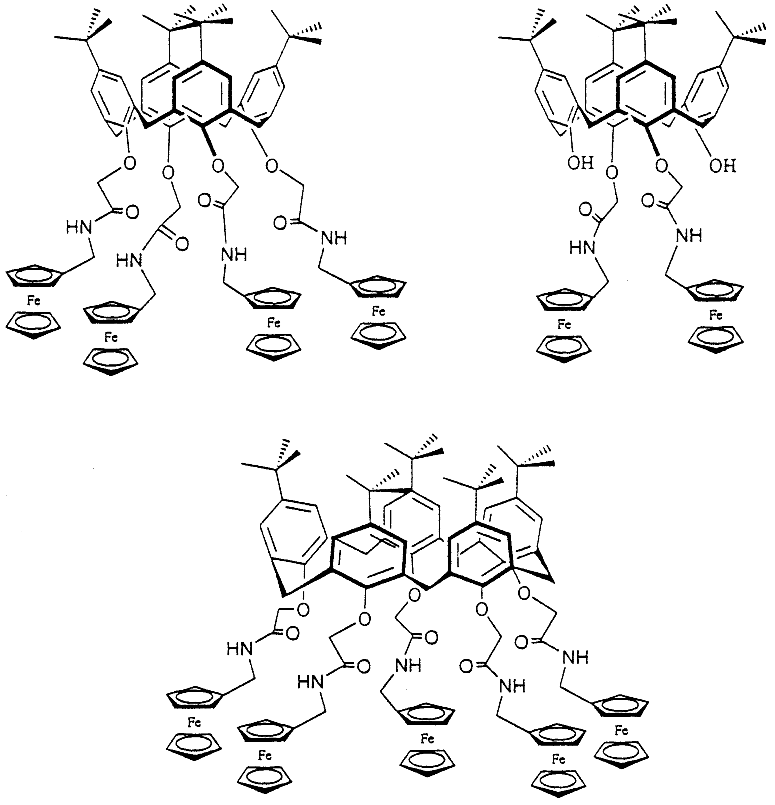


Fig. 11. Lower rim calixarene ferrocene receptors.

Table 8 shows the results for **(33)** at pH 7 where good agreement between the concentrations of phosphate calculated by the electrochemical experiments in the presence and absence of sulphate was found.

The guanidinium moiety appended to ferrocene has also been employed in sensing anions [29]. It has the added bonus over polyammonium receptors in that this group is practically pH-independent. It has been shown that receptor **(37)** binds and senses pyrophosphate in methanol-water mixtures giving cathodic shifts of up to 70 mV in the ferrocene redox wave (Fig. 15).

3. Luminescent sensing of anions by ruthenium(II) bipyridyl based receptor systems

The high sensitivity of sensing target guest species via fluorescent techniques has stimulated an enormous amount of interest in the covalent attachment of organic and inorganic luminophores in close proximity to charged guest recognition sites [30]. Examples of luminescent anion responsive systems have combined the anthra-

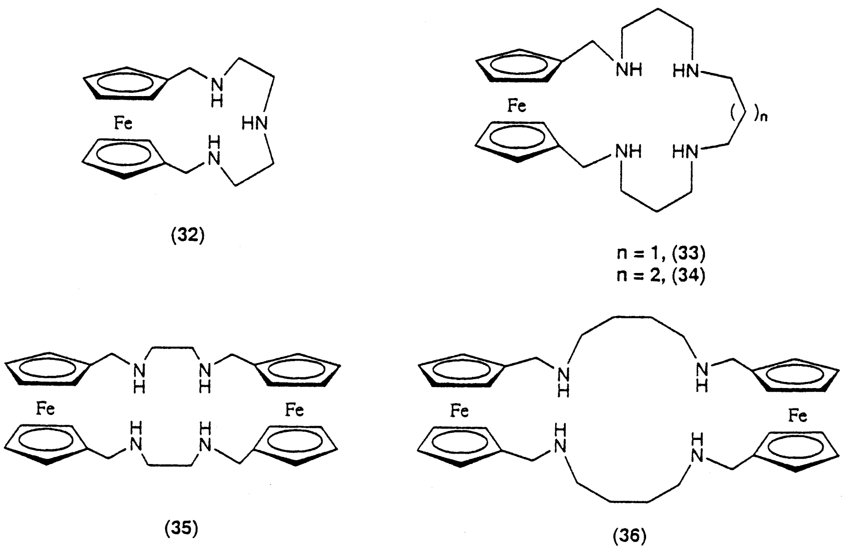


Fig. 12. Examples of water soluble ferrocene-amine receptors.

cene fluorophore with polyammonium [31], guanidinium [32] and zinc(II) amine [33] anion recognition sites. Recently cyclen appended phenanthridinium europium and terbium complexes have shown to sense halide and hydroxide ions in water [34,48]. Further in depth reviews of these systems are described within this review volume.

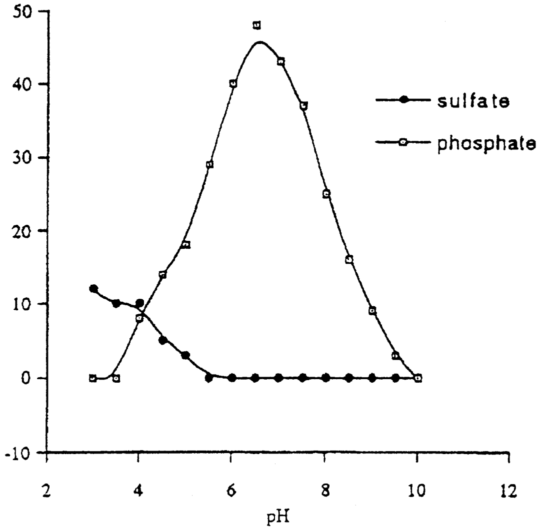


Fig. 13. Change in half-wave potential versus pH for (**33**) with phosphate and sulphate.

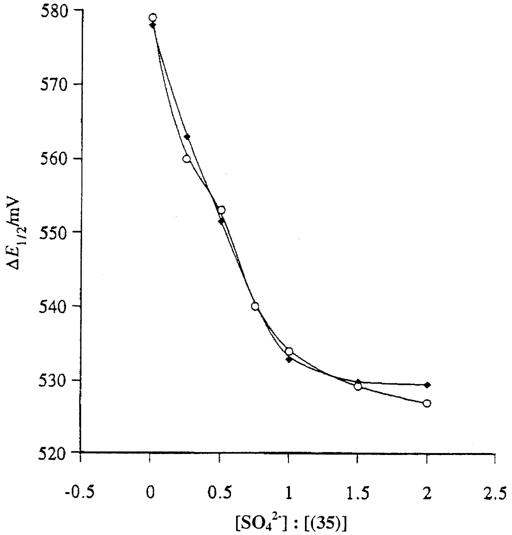


Fig. 14. An example of a calibration curve. Redox potential shift ($\Delta E_{1/2}$) of (**35**) versus sulfate-to-(**35**) ratios in the absence, ○; and presence of phosphate, ◆.

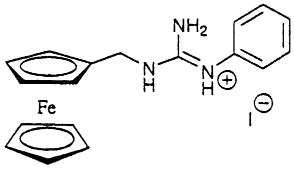
Table 8
Determination of the concentration of phosphate in the presence of sulfate with **(33)** in water at pH 7.0 by using electrochemical methods[a]

[Phosphate] × 10^5		[Phosphate] × 10^5	
14 (2)[a]	[14][b]	15 (1)[c]	[15][b]
27 (2)	[27]	27 (2)	[29]
39.1 (9)	[39.0]	41 (2)	[42]

[a] Concentration (mol dm^{-3}) 0.1M KNO_3. Values in brackets are the standard deviations in the last significant figure, determined by electrochemical calibration curves.

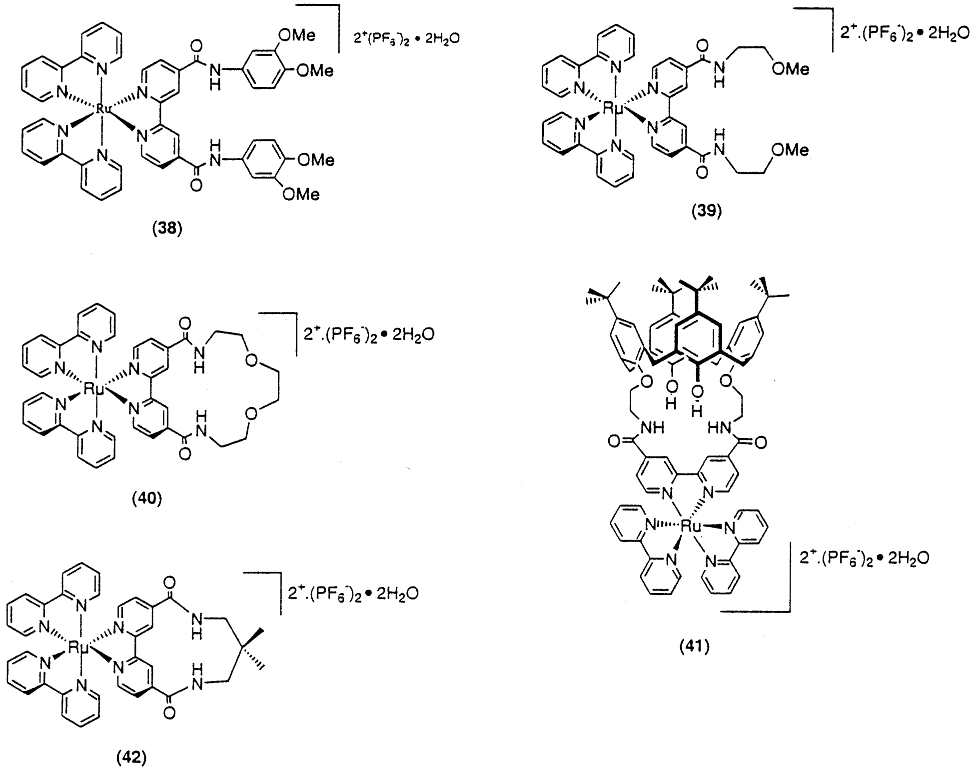
[b] Phosphate concentration (mol dm^{-3}).

[c] [Phosphate] (mol dm^{-3}) determined in the presence of sulphate [sulphate] = 52×10^{-5} mol dm^{-3}.



(37)

Fig. 15. An example of a ferrocene–guanidium receptor.



(38)

(39)

(40)

(41)

(42)

Fig. 16. Ruthenium(II)bipyridyl receptors.

Ruthenium(II) tris(2,2′-bipyridyl) has been one of the most extensively investigated complexes due to its chemical stability, redox properties, excited state reactivity, and luminescent emission [35,49]. We have incorporated the ruthenium(II) bipyridyl moiety into acyclic, macrocyclic and calix[4]arene structural frameworks to produce a new class of anion receptor capable of optical and electrochemical sensing (Fig. 16) [36,50,37]. Single crystal X-ray structures of the chloride complex of **(38)** (Fig. 17) and the $H_2PO_4^-$ complex of **(41)** highlight the importance of hydrogen bonding to the anion complexation process. Stability constant determinations in DMSO demonstrated that the acyclic receptors form strong complexes with Cl^- and $H_2PO_4^-$. The macrocyclic and calix[4]arene receptors **(40)–(42)** form highly selective and thermodynamically stable complexes with $H_2PO_4^-$. Electrochemical anion recognition experiments showed substantial anion induced cathodic perturbation of the ligand centred amide substituted 2,2′-bipyridine reduction redox couple. These perturbations were in agreement with stability constant values, with **(41)** sensing $H_2PO_4^-$ in the presence of ten-fold excess of HSO_4^- and Cl^-, Fluorescence emission measurements were also undertaken to probe the anion binding process. All receptors exhibited significant blue shifts in the metal-ligand charge transfer (MLCT) λ_{max} emission band on addition of Cl^- and $H_2PO_4^-$, with **(41)**

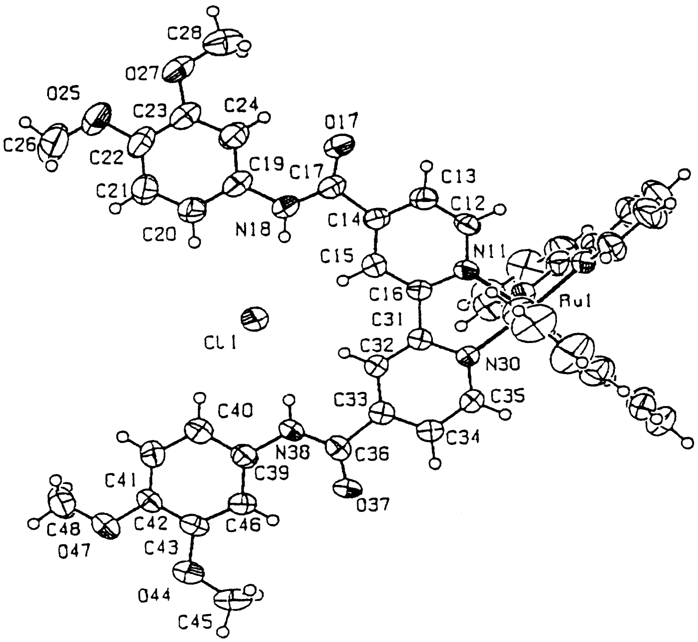


Fig. 17. The X-ray determined crystal structure of (**38**) with chloride as the guest.

displaying the largest perturbation (16 nm) (Fig. 18). These shifts are *not* observed with unfunctionalised $[Ru(bpy)_3]^{2+}$ and were accompanied by large increases in emission intensity (higher quantum yields). It was proposed that this could be due to the bound anion rigidifying the receptor and inhibiting vibrational and rotational relaxation modes of non-radiative decay.

An acyclic mixed-ruthenium(II) bpy-ferrocene receptor **(43)** whose emission of the ruthenium centre in the free receptor is quenched by the ferrocene units has also

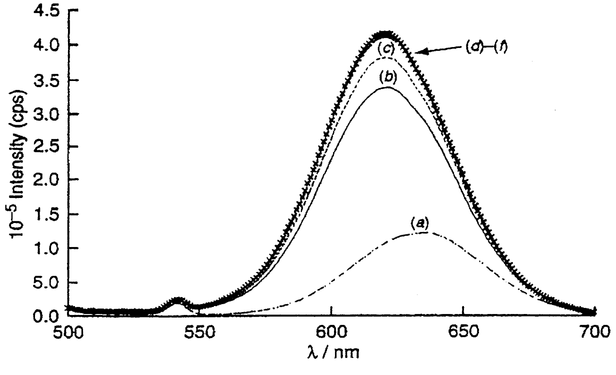
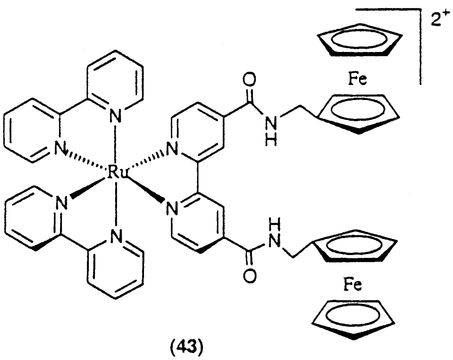


Fig. 18. Flourescence enhancement of (**41**) on addition of stoichiometric amounts of $H_2PO_4^-$ in DMSO, (a) 0; (b) 3; (c) 6; (d) 9; (e) 12; (f) 15 equivalents of $H_2PO_4^-$.



(43)

Fig. 19. Ruthenium(II) bipyridyl-ferrocene receptor.

been prepared by our group (Fig. 19) [38]. Interestingly the addition of $H_2PO_4^-$ switches on the emission via a 20-fold increase. This effect was not observed with Cl^- or HSO_4^- ions. A competition experiment conducted in the presence of five equivalents of both Cl^- and HSO_4^- reproduced the emission increase on addition of $H_2PO_4^-$ confirming the property of **(43)** as a $H_2PO_4^-$ selective luminescent anion sensor.

Other mixed-metal receptors have included the cleft-type employing the d^6 metals of $Ru^{(II)}$, $Os^{(II)}$ and $Re^{(I)}$ [39] (Fig. 20).

These, like the previous examples, display dihydrogenphosphate selectivity over chloride. Strength of binding can be tuned by choice of the spacer/bridging moiety to quite a dramatic effect. For example the phenyl-bridged ligand has a stability

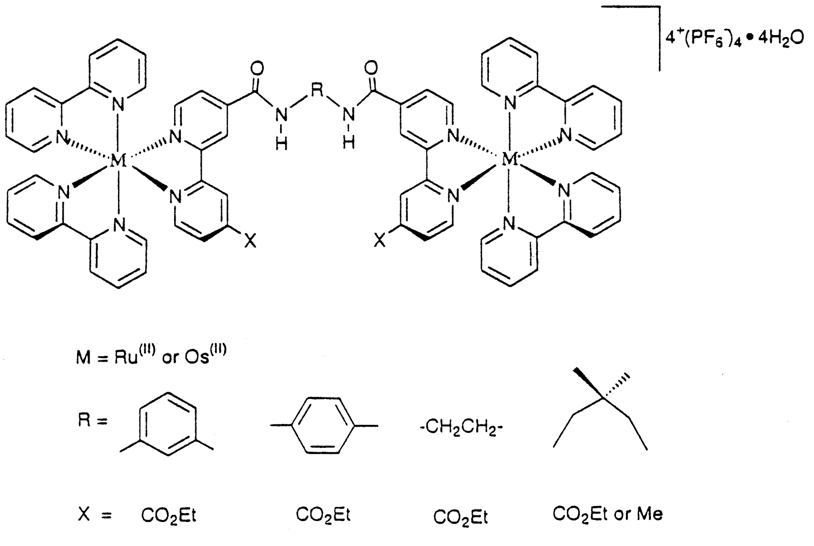


Fig. 20. Cleft-type receptors selective for phosphate.

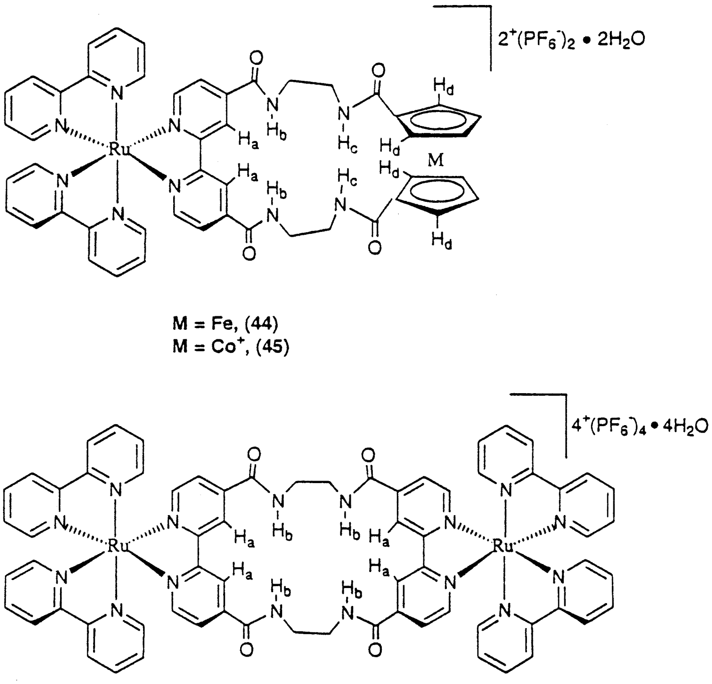
constant with dihydrogenphosphate of 55 M^{-1} for the *m*-phenylene version but $K = 4320\ M^{-1}$ for the *para*- analogue in DMSO-d_6.

Others spacers were utilised, such as ethyl and 2,2′-dimethylpropyl. The receptors with $Os^{(II)}$ displayed larger anion stability constants indicating the efficient Lewis acidic character of the $Os(bpy)_3^{2+}$ moiety.

It is noteworthy that few of the receptors discussed so far exhibit specific binding and sensing of the chloride anion. We have recently prepared the macrocylic receptors **(44)–(46)** (Fig. 21) which exhibit extremely stable 1:1 stoichiometric binding of chloride in DMSO-d_6 with stability constants of up to $4 \times 10^4\ M^{-1}$ [40].

No evidence for binding of the $H_2PO_4^-$ was observed from ^1H and ^{31}P NMR experiments. This remarkable selectivity may be attributed to the inherently rigid structures of the macrocycles as the acyclic analogue binds the $H_2PO_4^-$ more strongly than Cl^-. The larger size and tetrahedral shape of $H_2PO_4^-$ make this anion non-complementary for the receptor's cavity. Fluorescence studies indicated a blue-shift response to chloride with significant intensity enhancement but no response to $H_2PO_4^-$. Interestingly increasing the size of the macrocyclic cavity by two or four methylene units dramatically reverses the anion selectivity trend.

The neutral isoelectronic rhenium(I) bipyridyl amide receptors have been prepared and shown to selectively bind and optically sense via MLCT enhancement acetate anions in DMSO solutions [41] (Fig. 22). The mixed Re(I)-Pd(II) metal



M = Fe, (44)
M = Co+, (45)

(46)

Fig. 21. Macrocyclic halide-selective receptors.

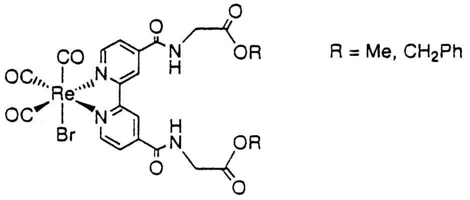


Fig. 22. Rhenium (I) bipyridyl amide receptors.

macrocycle (Fig. 23) binds the perchlorate anion which also results in significant MLCT enhancement in acetone solutions [42].

Water soluble ruthenium(II) bipyridyl polyaza receptors have very recently been prepared [43] and shown to bind and detect phosphate anions in aqueous media via MLCT luminescent emission quenching (Fig. 24). Using potentiometric techniques, it was shown that these systems bind phosphate anions ($H_2PO_4^-$, ATP^{2-}) with log *K*'s in the region of 3–5 in water at 25°C with KNO_3 as supporting electrolyte.

Initial fluorescence studies were concerned with titrations against pH. Samples were acidified to pH ≈ 2 and then titrated with dilute base, following the ^{3}MLCT emission maximum at 600–630 nm. For compounds **(47)**, **(48)** and **(49)** the emission intensity increased upon basification to a maximum around pH 5–6 after which the intensity decreased again. In conjunction with this there was a blue shift of 20 nm, from 625 nm at pH ≤ 4 to 605 nm at basic pH values (Fig. 25).

At higher pH values the unprotonated nitrogens (between 2 and 4 of them) can quench the luminescence via photoinduced electron transfer (PET). This mechanism is removed however as successive protonation steps occur up to pH ≈ 6.

Hereafter the quenching returns but in the possible guise of Ru-N bond fission caused by proximal positive charges to the $Ru(bpy)_3^{2+}$ [44].

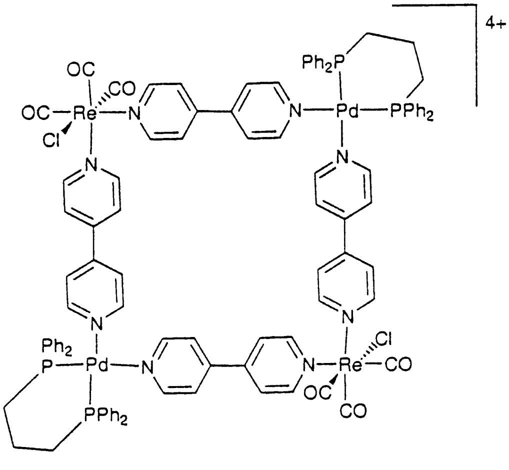
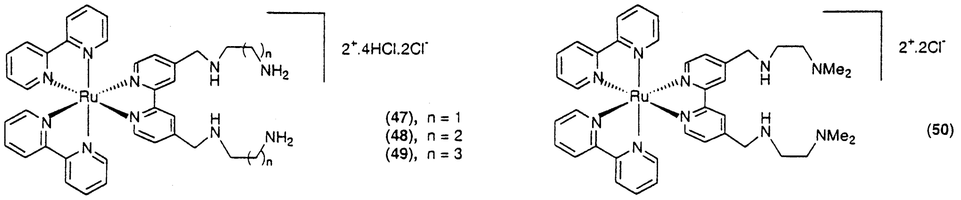


Fig. 23. Rhenium (I)–Paladium (II) macrocycle.



(47), n = 1
(48), n = 2
(49), n = 3

(50)

Fig. 24. Water-soluble ruthenium(II) amine receptors for biologically important anions.

For **(50)** the same situation applies at pH ≤ 5.5. However at higher pHs there is no return of quenching but a steady increase in emission intensity. This situation could arise from the fact that the pK_as of this receptor are far lower than for its analogues, in other words it is more acidic. The difference in energy levels between

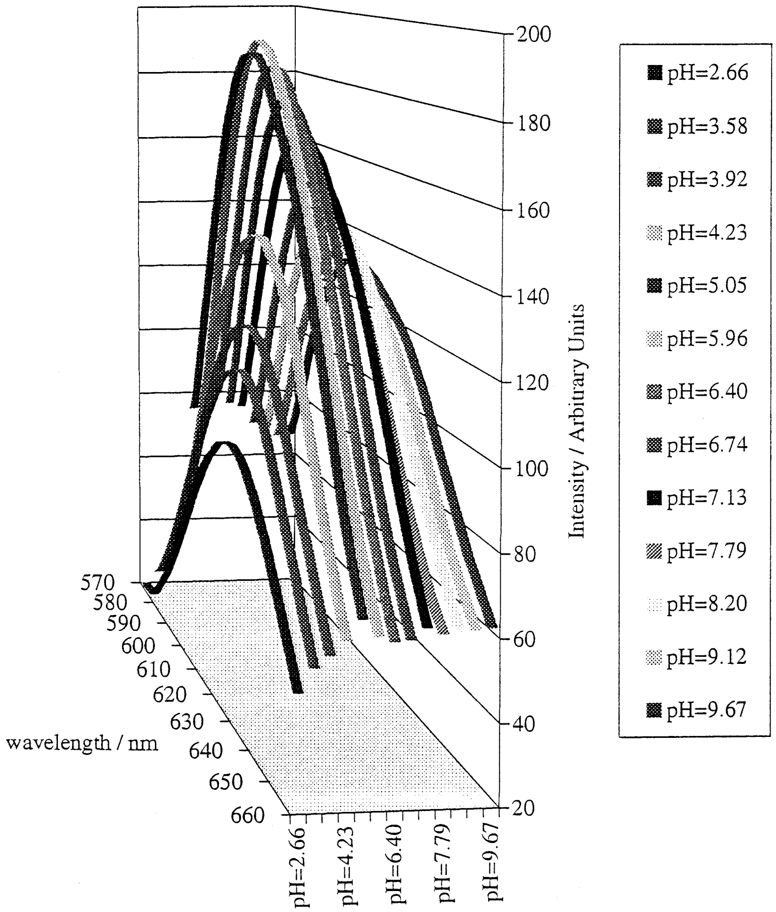


Fig. 25. Flourescence intensity versus pH and wavelenght for (**47**).

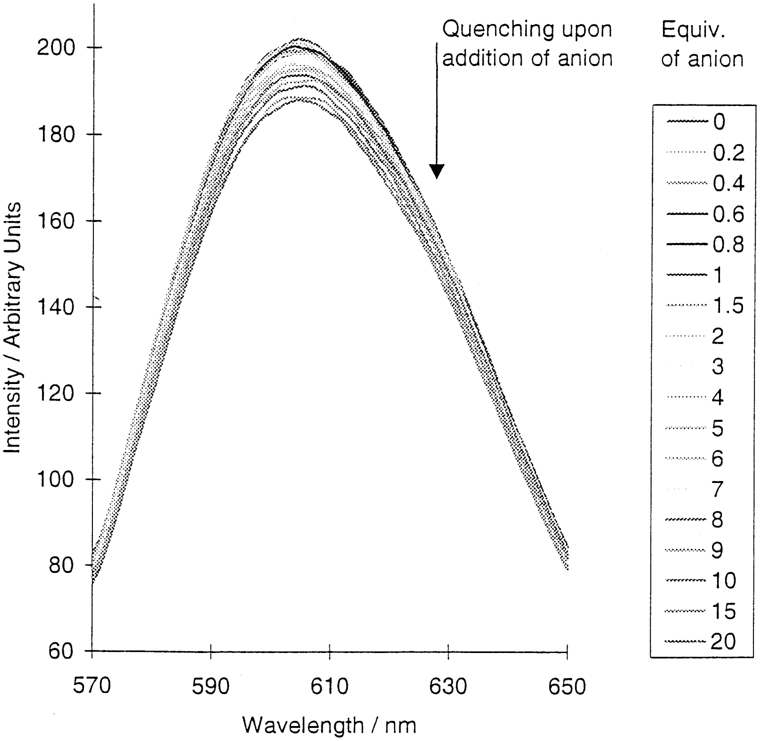


Fig. 26. Flourescence quenching of (**47**) in H_2O at 25°C, bufered with *N*-morpholinoethylsulfonic acid (MES) to pH = 6.02, titrated with KH_2PO_4.

the lone pairs of these more acidic amine nitrogens and the excited ^{3}MLCT state of the Ru could be large enough to prevent effective quenching via a PET mechanism.

Titrations with KH_2PO_4 and Na_2H_2ATP into non-deaerated buffered water solutions of these four ligands at pH 6 produced quenching by 15% (Fig. 26).

4. Conclusions

This review has described a variety of transition metal organometallic and coordination receptor systems which are capable of recognising and sensing anionic guest species in organic and aqueous media by electrochemical and optical methods. Generally it is possible to rationalise the observed anion thermodynamic stability and selectivity trends of these systems on the basis of complementary receptor-anion guest size, binding site topology and anion bascity. Solvation effects are also of crucial importance to the anion recognition event. However, the paucity of enthalpic and entropic data negates discussion of solvation effects on these systems [22] and also in the field of anion coordination chemistry as a whole [8,45]. Regarding sensitivity of electrochemical and optical anion detection the nature of the redox-active/photo-active transition metal reporter group and its proximity to the anion binding site clearly dictates the receptor's sensing proficiency. Future fabrication of these types of systems into electronically conducting polymeric supports and optical fibres will no doubt lead to actual prototype sensory devices of commercial usage.

References

[1] J.J.R. Frausto-da-Silva, R.J.P. Williams, Struct. Bonding 29 (1976) 67.
[2] P.M. Quinton, FASEB J. 4 (1990) 2709.
[3] K. Renkawek, G.J.C.G.M. Bosman, Neuroreport 6 (1995) 929.
[4] R.M. Harrison, Pollution: Causes, Effects and Control, RSC, London, 1983.
[5] E. Holm, Radiochim. Acta 63 (1993) 57.
[6] C.H. Park, H.E. Simmons, J. Am. Chem. Soc. 90 (1968) 2431.
[7] P.D. Beer, D.K. Smith, Prog. Inorg. Chem. 46 (1997) 1.
[8] Bianchi, Bowman-James, Garcia-Espana, Supramolecular Chemistry of Anions, Wiley-VCH, New York, 1997.
[9] J. Scheerder, J.F.J. Engbersen, D.N. Reinhoudt, Recueil des Travaux Chimiques des Pays-Bas, 115 (1996) 307.
[10] F.P. Schmidtchen, M. Berger, Chem. Rev. 97 (1997) 1609.
[11] H.-J. Schneider, Angew. Chem. Int. Ed. Engl. 30 (1991) 1417.
[12] P.D. Beer, P.A. Gale, G.Z. Chen, J. Chem. Soc. Dalton Trans. (1999) 1897.
[13] P.D. Beer, A.D. Keefe, J. Organomet. Chem. 375 (1989) C40.
[14] P.D. Beer, Chem. Commun. (1996) 689.
[15] P.D. Beer, D. Hesek, J.E. Kingston, D.K. Smith, S.E. Stokes, M.G.B. Drew, Organometallics 14 (1995) 3288.
[16] P.D. Beer, M.G.B. Drew, D. Hesek, M. Shade, F. Szemes, Chem. Comm. (1996) 2161.
[17] D. Dolphin, The Porphyrins, Academic Press, New York, 1978.
[18] P.D. Beer, M.G.B. Drew, D. Hesek, R. Jagessar, Chem. Commun. (1995) 1187.
[19] P.D. Beer, S. Stokes, Polyhedron 14 (1995) 2631.
[20] P.D. Beer, Z. Chen, M.G.B. Drew, J. Kingston, M. Ogden, P. Spencer, Chem. Commun. (1993) 1046.
[21] M.E. Padilla-Tosta, R. Martinez-Manez, T. Pardo, J. Soto, M.J.L. Tendero, Chem. Commun. (1997) 887.
[22] P.D. Beer, A.R. Graydon, A.O.M. Johnson, D.K. Smith, Inorg. Chem. 36 (1997) 2112.
[23] P.D. Beer, M.G.B. Drew, R. Jagessar, J. Chem. Soc. Dalton Trans. (1997) 881.
[24] J.E. Kingston, L. Ashford, P.D. Beer, M.G.B. Drew, J. Chem. Soc. Dalton Trans. (1999) 251.
[25] C. Valéro, J.-L. Fillaut, J. Ruiz, J. Guittard, J.-C. Blais, D. Astruc, J. Am. Chem. Soc. 119 (1997) 2588.
[26] P.A. Gale, Z. Chen, M.G.B. Drew, J.A. Heath, P.D. Beer, Polyhedron 17 (1998) 405.
[27] P.D. Beer, Z. Chen, M.G.B. Drew, A.O.M. Johnson, D.K. Smith, P. Spencer, Inorg. Chim. Acta 246 (1996) 143.
[28] P.D. Beer, J. Cadman, J.M. Llloris, R. Martínez-Máñez, M.E. Padilla-Tosta, T. Pardo, D.K. Smith, J. Soto, J. Chem. Soc. Dalton Trans. (1999) 127.
[29] P.D. Beer, M.G.B. Drew, D.K. Smith, J. Organomet. Chem. 543 (1997) 259.
[30] A.P. de Silva, H.Q.N. Gunaratne, T. Gunnlaugsson, A.J.M. Huxley, C.P. McCoy, J.T. Rademacher, et al., Chem. Rev. 97 (1997) 1515.
[31] A.W. Czarnik, Acc. Chem. Res. 27 (1994) 302.
[32] A.P. de Silva, H.Q.N. Guarantee, C. McVeigh, M.G.E. Maguire, P.R.S. Maxwell, E. O'Hanlon, Chem. Commun. (1996) 2191.

[33] L. Fabbrizzi, G. Francese, M. Licchelli, A. Perotti, A. Taglietti, Chem. Commun. (1997) 581.
[34] D. Parker, K. Senanayake, J.A.G. Williams, J. Chem. Soc. Perkin Trans. 2 (1998) 2129.
[35] V. Balzanni, F. Barigeletti, L.D. Cola, Top. Curr. Chem. 158 (1990) 31.
[36] F. Szemes, D. Hesek, Z. Chen, S.W. Dent, M.G. B. Drew, A.J. Goulden, et al., Inorg. Chem. 35 (1996) 5868.
[37] P.D. Beer, Acc. Chem. Res. 31 (1998) 71.
[38] P.D. Beer, A.R. Graydon, L.R. Sutton, Polyhedron 15 (1996) 2457.
[39] P.D. Beer, S.W. Dent, G.W. Hobbs, T. Wear, Chem. Commun. (1997) 99.
[40] P.D. Beer, F. Szemes, V. Balzani, C.M. Sala, M.G. B. Drew, S.W. Dent, M. Maestri, J. Am. Chem. Soc. 119 (1997) 11864.
[41] P.D. Beer, R. Wilson (unpublished results).
[42] R.V. Slone, D.I. Yoon, R.M. Calhoun, J.T. Hupp, J. Am. Chem. Soc. 117 (1995) 11813.
[43] P.D. Beer, J. Cadman, New J. Chem. 23 (1999) 347.
[44] R. Grigg, W.D.J.A. Norbert, J. Chem. Soc. Chem. Commun. (1992) 1300.
[45] M. Berger, F.P. Schmidtchen, Angew. Chem. Int. Ed. 37 (1998) 2694.
[46] P.D. Beer, P.A. Gale, G.Z. Chen, Adv. Phys. Organ. Chem. 31 (1998) 1.
[47] P.D. Beer, M.G.B. Drew, D. Hesek, K.C. Nam, Chem. Comm. (1997) 107.
[48] D. Parker, K. Senanayake, J.A.G. Williams, Chem. Commun. (1997) 1777.
[49] A. Juris, V. Balzani, F. Barigeletti, S. Campagna, P. Belser, A.v. Zelewsky, Coord. Chem. Rev. 84 (1988) 85.
[50] P.D. Beer, S.W. Dent, T. Wear, J. Chem. Soc. Dalton Trans. (1996) 2341.