Synthesis and Characterization of Novel Acyclic, Macrocyclic, and Calix[4]arene Ruthenium(II) Bipyridyl Receptor Molecules That Recognize and Sense Anions

Fridrich Szemes,[†] Dusan Hesek,[†] Zheng Chen,[†] Simon W. Dent,[†] Michael G. B. Drew,[‡] Alistair J. Goulden,[†] Andrew R. Graydon,[†] Alan Grieve,[†] Roger J. Mortimer,[§] Trevor Wear,[||] John S. Weightman,[§] and Paul D. Beer*,[†]

Inorganic Chemistry Laboratory, University of Oxford, South Parks Road, Oxford OX1 3QR, U.K., Department of Chemistry, University of Reading, Whiteknights, Reading RG6 2AD, U.K., Department of Chemistry, Loughborough University of Technology, Loughborough, Leicestershire LE11 3TU, U.K., and Kodak Limited, Headstone Drive, Harrow, Middlesex HA1 4TY, U.K.

Received March 22, 1996[⊗]

The Lewis acidic redox-active and photoactive ruthenium(II) bipyridyl moiety in combination with amide (CO−NH) groups has been incorporated into acyclic, macrocyclic, and lower rim calix[4]arene structural frameworks to produce a new class of anion receptor with the dual capability of sensing anionic guest species via electrochemical and optical methodologies. Single-crystal X-ray structures of (**1**)Cl and (**11**)H_2PO_4 reveal the importance of hydrogen bonding to the overall anion complexation process. In the former complex, six hydrogen bonds (two amide and four C−H groups) stabilize the Cl^- anion and three hydrogen bonds (two amide and one calix[4]arene hydroxyl) effect $H_2PO_4^-$ complexation with **11**. Proton NMR titration investigations in deuterated DMSO solutions reveal these receptors form strong and, in the case of the macrocyclic **5** and calix[4]arene-containing receptor **11**, highly selective complexes with $H_2PO_4^-$. Cyclic and square-wave voltammetric studies have demonstrated these receptors to electrochemically recognize Cl^-, Br^-, $H_2PO_4^-$, and HSO_4^- anions. The calix[4]arene anion receptor **11** selectively electrochemically senses $H_2PO_4^-$ in the presence of 10-fold excess amounts of HSO_4^- and Cl^-. Fluorescence emission spectral recognition of $H_2PO_4^-$ in DMSO solutions is displayed by **3**, **5**, and **11**.

Introduction

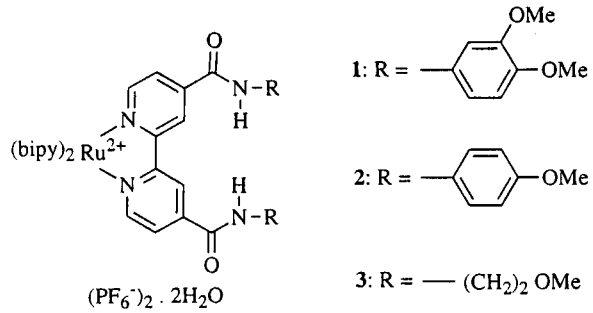
Stimulated by how Nature utilizes negatively charged species for numerous biochemically important pathways and polyanions for the storage and transmission of genetic information, the molecular recognition of anionic guest molecules by positively charged or electron deficient neutral abiotic organic receptor molecules is an area of intense current interest.[1] Examples of anion receptors reported to date include Lewis acid tin-,[2] mercury-,[3] silicon-,[4] uranyl-containing[5] ligands, macropolycyclic ammonium quaternary salts,[6] protonated polyammonium[7] and expanded porphyrin macrocycles,[8] and guanidinium derivatives.[9] Surprisingly however, the design and syntheses of specific ligands that have the capability of optically[10] and/or electrochemically[11] detecting anions in aqueous and nonaqueous media are extremely rare. Czarnik and co-workers[12] recently described the only anion fluorescent responsive type, based on acyclic anthracene appended polyammonium receptors. We have reported the first classes of redox-responsive anion receptors that contain positively charged or neutral amide (CO−NH)-linked cobaltocenium[13] and ferrocene[14] organometallic moieties, which can electrochemically recognize halide, nitrate, hydrogen sulfate, and dihydrogen phosphate anions in polar solvents. In addition, water-soluble polyammonium ferrocene macrocyclic receptors can bind and sense ATP and HPO_4^{2-} phosphate anions in the aqueous environment.[14]

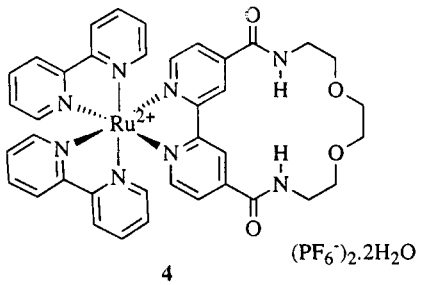
* To whom correspondence should be addressed. email: beer%server.icl@ox.ac.uk.
[†] University of Oxford.
[‡] University of Reading.
[§] Loughborough University of Technology.
[||] Kodak Limited.
[⊗] Abstract published in *Advance ACS Abstracts,* September 1, 1996.

(1) (a) Schmidtchen, F. P. *Nachr. Chem., Tech. Lab.* **1988**, *8*, 10. (b) Katz, H. E. In *Inclusion Compounds*; Atwood, J. L., Davies, J. E. D., MacNicol, D. D., Eds.; Academic Press: New York, 1991; Vol. 4, p 391. (c) Dietrich, B. *Pure Appl. Chem.* **1993**, *65*, 1457.
(2) (a) Newcomb, M.; Madonik, A. M.; Blanda, M. T.; Judice, J. K. *Organometallics* **1987**, *6*, 145. (b) Newcomb, M.; Homer, J. H.; Blanda, M. T. *J. Am. Chem. Soc.* **1987**, *109*, 7878.
(3) (a) Wuest, J. D.; Zacharie, B. *Organometallics* **1985**, *4*, 410. (b) Wuest, J. D.; Beauchamp, A. L.; Olivier, M. J.; Zacharie, B. *J. Am. Chem. Soc.* **1986**, *108*, 73. (c) Hawthorne, M. F.; Yang, X.; Knobler, C. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 1507.
(4) Jung, M. E.; Xia, H. *Tetrahedron. Lett.* **1988**, *29*, 297.
(5) (a) Reinhoudt, D. N.; Rudkevich, D. M.; Stauthamer, W. R. P. V.; Verboom, W.; Engersen, J. F. J.; Harkema, S. *J. Am. Chem. Soc.* **1992**, *114*, 9671. (b) *J. Am. Chem. Soc.* **1994**, *116*, 4341.
(6) (a) Schmidtchen, F. P. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 720. (b) *Tetrahedron Lett.* **1986**, *27*, 1987. (c) *J. Am. Chem. Soc.* **1986**, *108*, 8249. (d) Beer, P. D.; Wheeler, J. W.; Grieve, A.; Moore, C.; Wear, T. *J. Chem. Soc., Chem. Commun.* **1992**, 1225.
(7) (a) Park, C. H.; Simmons, H. E. *J. Am. Chem. Soc.* **1968**, *90*, 2431. (b) Lehn, J.-M.; Graf, E. *J. Am. Chem. Soc.* **1976**, *98*, 6403. (c) Dietrich, B.; Hosseini, M. W.; Lehn, J.-M.; Sessions, R. B. *J. Am. Chem. Soc.* **1981**, *103*, 1282. (d) Hosseini, M. W.; Blacker, A. J.; Lehn, J.-M. *J. Am. Chem. Soc.* **1990**, *112*, 3896 and references therein.
(8) (a) Sessler, J. L.; Moody, J. D.; Ford, D. A.; Lynch, V. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 452. (b) Sessler, J. L.; Burrell, A. K. *Top. Curr. Chem.* **1992**, *161*, 177.
(9) (a) Dietrich, B.; Fyles, T. M.; Lehn, J.-M.; Pease, L.; Fyles, D. L. *J. Chem. Soc., Chem. Commun.* **1978**, 934. (b) Galan, A.; Pueyo, E.; Salmerón, A.; De Mendoza, J. *Tetrahedron Lett.* **1991**, *32*, 1827. (c) Schiessl, P.; Schmidtchen, F. P. *Tetrahedron Lett.* **1993**, *34*, 2449 and references therein.
(10) (a) Huston, M. E.; Akkaya, E. U.; Czarnik, A. W. *J. Am. Chem. Soc.* **1989**, *111*, 8735. (b) Czarnik, A. W. *Acc. Chem. Res.* **1994**, *27*, 302.
(11) Beer, P. D. *Adv. Mater.* **1994**, *6*, 607 and references therein.
(12) Vance, D. H.; Czarnik, A. W. *J. Am. Chem. Soc.* **1994**, *116*, 9397.
(13) (a) Beer, P. D.; Hazlewood, C.; Hesek, D.; Hodacova, J.; Stokes, S. E. *J. Chem. Soc., Dalton Trans.* **1993**, 1327. (b) Beer, P. D.; Drew, M. G. B.; Graydon, A. R.; Smith, D. K.; Stokes, S. E. *J. Chem. Soc., Dalton Trans.* **1995**, 403.
(14) (a) Beer, P. D.; Chen, Z.; Drew, M. G. B.; Kingston, J.; Ogden, M.; Spencer, P. *J. Chem. Soc., Chem. Commun.* **1993**, 1046. (b) Beer, P. D.; Chen, Z.; Goulden, A. J.; Graydon, A. R.; Stokes, S. E.; Wear, T. *J. Chem. Soc., Chem. Commun.* **1993**, 1834.

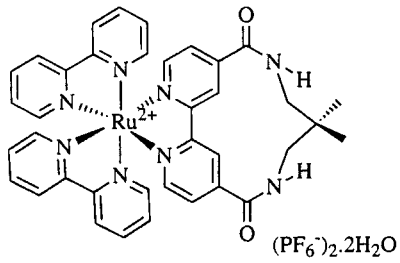
S0020-1669(96)00318-7 CCC: $12.00 © 1996 American Chemical Society

Table 1. Anion Receptors **1**−**5** and **11**−**13**

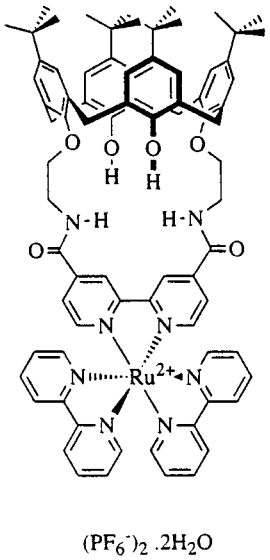




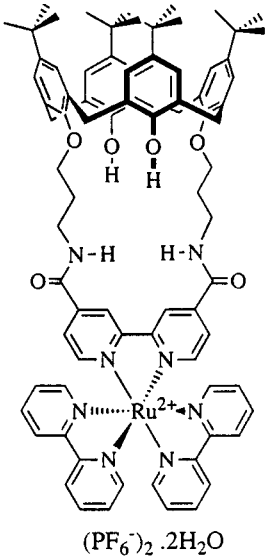
4



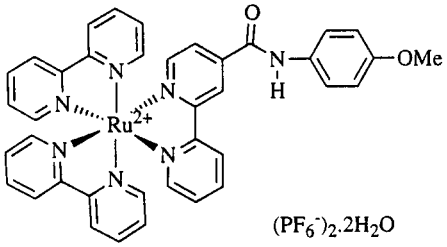
5



11



12



13

In the light of the crucial importance of hydrogen bonding to the anion recognition process for our metallocene organometallic receptors, we reasoned that in principle any Lewis acidic binding site in close proximity to one or more amide (CO−NH) groups may lead to the successful molecular recognition of an anionic guest species.[15] With this in mind, the Lewis acidic redox-active and photoactive ruthenium(II) bipyridyl moiety[16] in combination with amide groups is an attractive building block to utilize for the design and construction of innovative spectral and electrochemical sensory reagents for anions. In this paper, the preparation of novel acyclic, macrocyclic, and calix[4]arene ruthenium(II) bipyridyl anion receptor molecules (Table 1) is described, together with extensive anion coordination investigations using NMR spectroscopy, X-ray crystallography, fluorimetry, and cyclic and square-wave voltammetry.[17]

Results and Discussion

Synthesis of Anion Receptors. The new acyclic 4,4′-diamide-substituted bipyridine ligands were simply prepared in high yields via condensation reactions of 4,4′-bis(chlorocarbonyl)-2,2′-bipyridine[18] with appropriate primary aryl- and alkylamines. The ruthenium(II) complexes **1**−**3** were obtained by refluxing the appropriate bipyridine ligand with $[RuCl_2(bipy)_2]\cdot 2H_2O$ in a mixture of solvents, typically ethanol, acetic acid, and water, followed by purification on Sephadex LH-20 and precipitation of the complexes on addition of ammonium hexafluorophosphate.

The condensation of 4,4′-bis(chlorocarbonyl)-2,2′-bipyridine with the diamines 2,2′-(ethylenedioxy)diethylamine and 2,2-dimethyl-1,3-diaminopropane gave new macrocyclic ligands. The corresponding ruthenium(II) complexes **4** and **5** were prepared using the standard procedure previously described for the acyclic analogues.

The calixarenes[19] are attractive host molecules on which to construct additional recognition sites for target guests. Although the calix[4]arene host structural unit has been modified primarily at the lower rim for the recognition of metal cations,[20] the design and synthesis of calix[4]arene *anion* receptors are still relatively rare.[21] Incorporating the ruthenium(II) bipyridyl moiety at the

(15) (a) Beer, P. D.; Dickson, C. A. P.; Fletcher, N. C.; Goulden, A. J.; Grieve, A.; Hodacova, J.; Wear, T. *J. Chem. Soc., Chem. Commun.* **1993**, 828. (b) Beer, P. D. In *Transition Metals in Supramolecular Chemistry*; Fabrizzi, L., Poggi, A., Eds.; NATO ASI Series C, No 448; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1994; p 33.

(16) Juris, A.; Balzani, V.; Barigelletti, F.; Campagna, S.; Belser, P.; von Zelewsky, A. *Coord. Chem. Rev.* **1988**, *84*, 85.

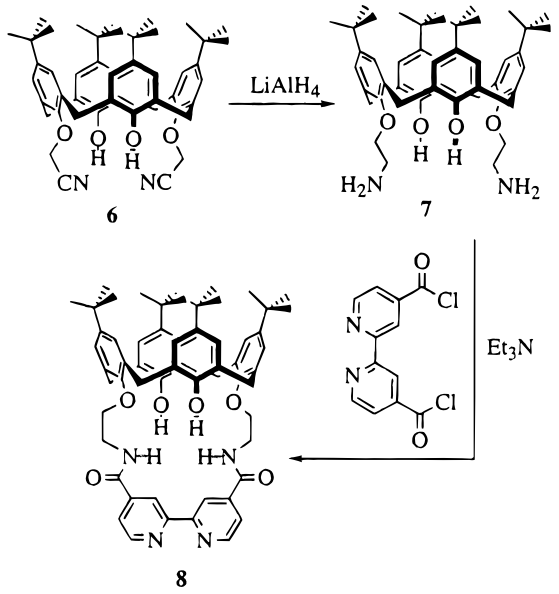
(17) Part of this work has been published as a preliminary communication: Beer, P. D.; Chen, Z.; Goulden, A. J.; Grieve, A.; Hesek, D.; Szemes, F.; Wear, T. *J. Chem. Soc., Chem. Commun.* **1994**, 1269.

(18) Whittle, C. P. *J. Heterocycl. Chem.* **1977**, *14*, 191.

(19) Gutsche, C. D. In *Calixarenes*; Stoddart, J. F., Ed.; Monographs in Supramolecular Chemistry, Vol. 1; The Royal Society of Chemistry: Cambridge and London, 1989.

(20) (a) Ungaro, R.; Pochini, A. In *Calixarenes, a Versatile Class of Macrocyclic Compounds*; Vicens, J., Bohwer, V., Eds.; Kluwer: Dorchrecht, The Netherlands, 1990; p 133. (b) Arnaud-Neu, F.; Barrett, G.; Harns, S. J.; Owens, M.; McKervey, M. A.; Schwing-Weill, M. J.; Schwinté, P. *Inorg. Chem*. **1993**, *32*, 2644 and references therein.

Scheme 1



lower rim of the calix[4]arene building block was achieved using the following preparative routes.

Using $LiAlH_4$, reduction of the 1,3-distally substituted cyanomethyl calix[4]arene **6**[22] gave diamine **7**, which on condensation with 4,4′-bis(chlorocarbonyl)-2,2′-bipyridine under high dilution conditions, gave the novel lower rim 2,2′-bipyridyl-functionalized calix[4]arene receptor **8** in 18% yield (Scheme 1).

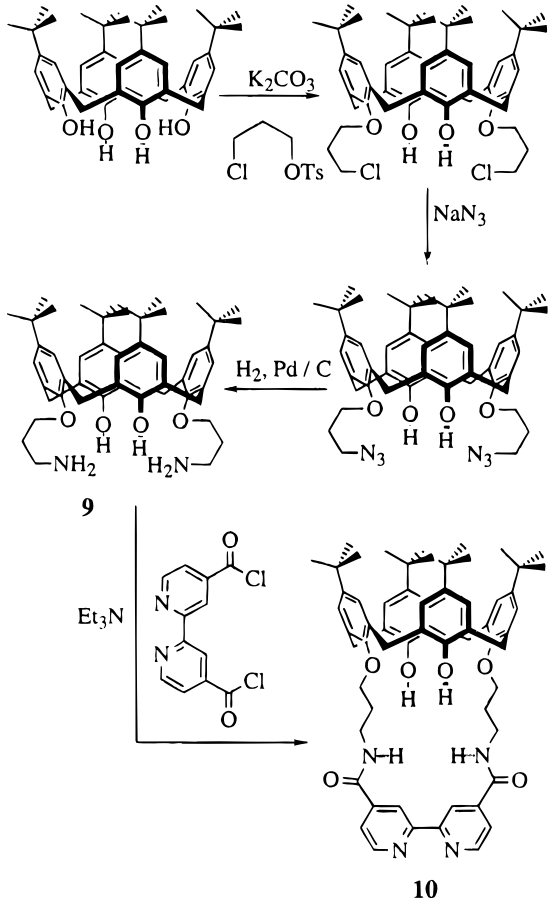
The new 1,3-distally substituted propyl-linked calix[4]arene diamine **9** was prepared in three steps via the reaction of the parent calix[4]arene with 3-chloropropyl tosylate in the presence of potassium carbonate, conversion of the bis(chloro) derivative to the corresponding azide, and catalytic hydrogenation (Scheme 2). A synthetic procedure analogous to that used for the preparation of **18** was used to produce the new lower rim compound **10** in 8% yield (Scheme 2).

The ruthenium(II) bipyridyl calix[4]arene complexes **11** and **12** were prepared by refluxing $[RuCl_2(bipy)_2]\cdot 2H_2O$ with the respective calix[4]arene receptor in ethanol, followed by purification on a Sephadex LH20 column and precipitation of the hexafluorophosphate complexes on addition of ammonium hexafluorophosphate.

A 4-amide-monosubstituted bipyridyl ligand was simply prepared via the condensation reaction of 4-(chlorocarbonyl)-2,2′-bipyridine with anisole and the ruthenium(II) complex **13** prepared using standard procedures.

Solid State Structures of Anion Complexes. Slow evaporation of an acetonitrile solution of **1** in the presence of chloride anions gave crystals suitable for an X-ray structural determination. The crystallographic data are summarized in Table 2. The structure contains a $[Ru(bipy\ amide)(bipy)_2]^{2+}$ cation together with an associated chloride ion encapsulated within it, as well as a disordered lattice chloride anion and assorted solvent. A view of the cation and enclosed chloride ion is

Scheme 2



shown in Figure 1. The ruthenium atom is six-coordinate, being bonded to six nitrogen atoms (at 2.006(5)−2.033(5) Å) from three bidentate ligands. There is no difference in the bond distances to the two types of bipy ligand. The coordination geometry is distorted octahedral, as is illustrated by the dimensions in Table 3. The Ru−N distances are in the expected range. The remaining dimensions in the cation are also unexceptional. Of particular interest is the position of the chloride anion which is encapsulated within the bipy amide ligand by forming six hydrogen bonds. It forms hydrogen bonds not only to the two N−H groups but also to four C−H groups. The H···Cl distances range from 2.51 to 2.71 Å, and the angles subtended at H are 148.0−162.8°. The chloride ion and six surrounding hydrogen atoms are closely planar with a maximum rms deviation of a contributing atom <0.12 Å. It is interesting that the encapsulation of the chloride ion does not require any significant distortion of the ligand; thus the NC−C−N torsion angle in the bipy amide is 6.4° compared to 0.0 and −1.6° in the two bipy ligands. The cations stack in pairs so that two adjacent bipy amide ligands overlap in a parallel fashion. The shortest C···C distance between layers is 3.40 Å, indicative of some significant interaction. There are also several independent acetonitrile solvent molecules in the unit cell, together with a disordered chloride anion, but these do not impact upon the conformation of the cation.

A solvent mixture of acetonitrile, ethanol, dimethyl sulfoxide, and water containing **11** and dihydrogen phosphate anions produced crystals suitable for X-ray structural analysis (Table 2). The structure contains two independent cations of formula $[Ru(\mathbf{8})(bipy)_2]^{2+}$ in the asymmetric unit. **8** consists of a calix[4]arene in the expected cone formation with the oxygen atoms in the 1- and 3-positions linked by a $-CH_2-CH_2-NH-CO-$(bipy)$-CO-NH-CH_2-CH_2$ chain. The two nitrogen atoms

(21) (a) Beer, P. D.; Drew, M. G. B.; Hazlewood, C.; Hesek, D.; Hodacova, J.; Stokes, S. E. *J. Chem. Soc., Chem. Commun.* **1993**, 229. (b) Xu, W.; Vittal, J. J.; Puddephatt, R. *J. Am. Chem. Soc.* **1993**, *115*, 6456. (c) Morzheim, Y.; Rudkevich, D. M.; Verboom, W.; Reinhoudt, D. N. *J. Org. Chem.* **1993**, *58*, 7602. (d) Rudkevich, D. M.; Verboom, W.; Reinhoudt, D. N. *J. Org. Chem.* **1994**, *59*, 3683. (e) Steed, J. W.; Junega, R. K.; Atwood, J. L. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 2456.

(22) Collins, E. M.; McKervey, M. A.; Madigan, E.; Moran, M.; Owens, M.; Ferguson, G.; Harris, S. J. *J. Chem. Soc., Perkin Trans. 1* **1991**, 3137.

Table 2. Crystal Data and Structure Refinement Details for the Chloride Complex of **1** and the Dihydrogen Phosphate Complex of **11**

	[Ru(bipy amide)(bipy)$_2$], 4.5MeCN, 2Cl$^-$	2[Ru(**8**)(bipy)$_2$]$^{2+}$, 2[H_2PO_4]$^-$, [HPO_4]$^{2-}$ 1.5EtOH, Me_2SO, 3MeCN, 4.5H_2O
empirical formula	$C_{57}H_{55.5}Cl_2N_{12.5}O_6Ru$	$C_{171}H_{205}N_{19}O_{31}P_3Ru_2$
fw	1183.61	3349.65
temp (K)	293 (2)	293(2)
wavelength (Å)	0.71070	0.71070
crystal system	triclinic	triclinic
space group	*P*1	*P*1
a (Å)	11.317(10)	15.865(8)
b (Å)	12.518(10)	23.591(11)
c (Å)	21.248(10)	32.512(12)
α (deg)	74.17(1)	104.92(1)
β (deg)	76.79(1)	99.85(1)
γ (deg)	82.63(1)	106.93(1)
V (Å^3)	2812	10842.2
Z	2	2
d(calcd) (Mg/m^3)	1.398	1.026
abs coeff (mm^{-1})	0.440	0.230
F(000)	1222	3522
crystal size (mm)	0.2 × 0.2 × 0.2	0.3 × 0.25 × 0.15
θ range for data collection (deg)	1.70−24.38	1.33−21.01
index ranges	$0 \le h \le 12$ $-14 \le k \le 14$ $-23 \le l \le 24$	$0 \le h \le 15$ $-23 \le k \le 22$ $-32 \le l \le 31$
no. of reflns collected	8260	20513
no. of parameters	679	1909
goodness-of-fit on F^2	1.023	0.812
final *R* indices [$I > 2\sigma(I)$]	R1 = 0.0741 wR2 = 0.1902	R1 = 0.1032 wR2 = 0.2652
R indices (all data)	R1 = 0.0953 wR2 = 0.2053	R1 = 0.1648 wR2 = 0.3421
largest diff peak and hole (e Å^{-3})	0.804 −0.746	1.212 −0.744

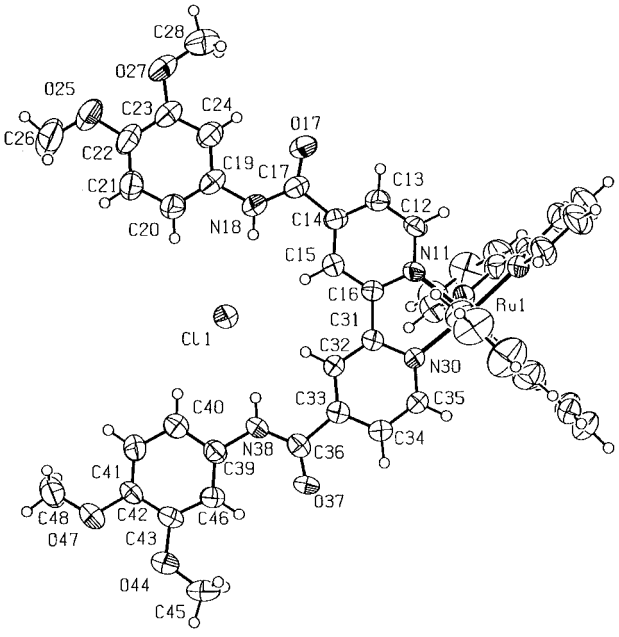


Figure 1. General view of (**5**)Cl$^-$, with thermal ellipsoids at 50% probability.

from the bipy ligand are directed away from the calix[4]arene and are therefore available for metal coordination to the ruthenium. The coordination sphere of the metal is completed by two bidentate bipy ligands. The structures of both cations

Table 3. Selected Molecular Dimensions in the Chloride Complex of **1** and the Dihydrogen Phosphate Complex of **11** (Bond Lengths, Å; Angles, deg)

Chloride Complex

Ru(1)−N(71)	2.006(5)	Ru(1)−N(61)	2.019(5)
Ru(1)−N(30)	2.017(4)	Ru(1)−N(82)	2.023(5)
Ru(1)−N(11)	2.018(5)	Ru(1)−N(50)	2.033(5)

N(71)−Ru(1)−N(30)	89.4(2)	N(11)−Ru(1)−N(82)	174.4(2)
N(71)−Ru(1)−N(11)	97.6(2)	N(61)−Ru(1)−N(82)	95.4(2)
N(30)−Ru(1)−N(11)	78.1(2)	N(71)−Ru(1)−N(50)	94.6(2)
N(71)−Ru(1)−N(61)	172.8(2)	N(30)−Ru(1)−N(50)	175.1(2)
N(30)−Ru(1)−N(61)	96.7(2)	N(11)−Ru(1)−N(50)	98.6(2)
N(11)−Ru(1)−N(61)	87.4(2)	N(61)−Ru(1)−N(50)	79.5(2)
N(71)−Ru(1)−N(82)	80.1(2)	N(82)−Ru(1)−N(50)	86.7(2)
N(30)−Ru(1)−N(82)	96.7(2)		

Dihydrogen Phosphate Complex

Molecule A

Ru(1)−N(61)	2.029(13)	Ru(1)−N(68)	2.058(12)
Ru(1)−N(88)	2.033(11)	N(158)−Ru(1)	2.014(9)
Ru(1)−N(91)	2.040(10)	N(162)−Ru(1)	2.057(9)

N(158)−Ru(1)−N(61)	173.7(4)	N(88)−Ru(1)−N(162)	94.1(4)
N(158)−Ru(1)−N(88)	87.8(4)	N(91)−Ru(1)−N(162)	172.8(5)
N(61)−Ru(1)−N(88)	97.3(5)	N(158)−Ru(1)−N(68)	96.4(4)
N(158)−Ru(1)−N(91)	97.6(4)	N(61)−Ru(1)−N(68)	78.7(5)
N(61)−Ru(1)−N(91)	86.9(4)	N(88)−Ru(1)−N(68)	173.6(5)
N(88)−Ru(1)−N(91)	79.3(5)	N(91)−Ru(1)−N(68)	95.3(5)
N(158)−Ru(1)−N(162)	79.2(4)	N(162)−Ru(1)−N(68)	91.4(4)
N(61)−Ru(1)−N(162)	96.8(4)		

Molecule B

N(158)−Ru(2)	2.037(11)	Ru(2)−N(81)	2.01(2)
N(160)−Ru(2)	2.065(11)	Ru(2)−N(68)	2.027(11)
Ru(2)−N(71)	1.989(14)	Ru(2)−N(88)	2.061(12)

N(71)−Ru(2)−N(81)	173.7(5)	N(68)−Ru(2)−N(88)	89.2(5)
N(71)−Ru(2)−N(68)	76.9(6)	N(158)−Ru(2)−N(88)	96.0(4)
N(81)−Ru(2)−N(68)	99.4(5)	N(71)−Ru(2)−N(160)	88.0(5)
N(71)−Ru(2)−N(158)	98.0(5)	N(81)−Ru(2)−N(160)	97.5(5)
N(81)−Ru(2)−N(158)	86.1(5)	N(68)−Ru(2)−N(160)	95.8(4)
N(68)−Ru(2)−N(158)	173.2(5)	N(158)−Ru(2)−N(160)	79.4(4)
N(71)−Ru(2)−N(88)	96.9(6)	N(88)−Ru(2)−N(160)	173.7(5)
N(81)−Ru(2)−N(88)	77.8(6)		

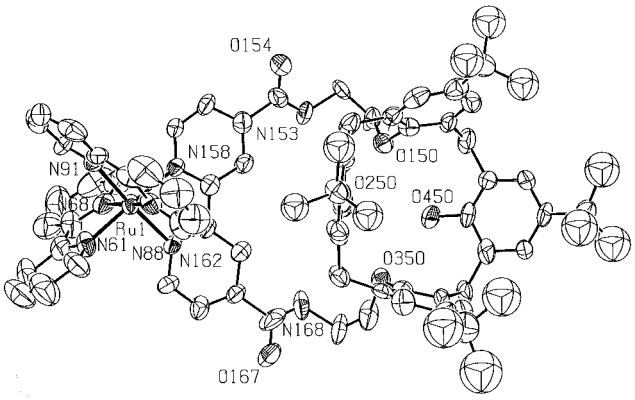


Figure 2. General view of [Ru(8)(bipy)$_2$]$^{2+}$ with thermal ellipsoids at 50% probability. This is cation A; the conformation of cation B is similar.

are similar, with Ru−N distances in the distorted octahedra ranging from 2.014(9) to 2.058(12) Å in one and from 1.989(14) to 2.065(11) Å in the other.

A general view of cation A is shown in Figure 2. The linkage of the calix[4]arene with the bipyridyl has had no major effect on the rigidity of the latter group. Thus N−C−C−N torsion angles in the complex are 4.5, −8.4° for the linked bipyridyl and −6.2, 1.6 and 0.2, −6.7° for the others. The conformation of the calix[4]arene in the two molecules is as expected. The usual hydrogen-bond pattern around the bottom of the cone is

Table 4. Details of Intermolecular Hydrogen Bonds in the Chloride Complex of **1** and the Dihydrogen Phosphate Complex of **11** (Å)

(a) Environment of the Encapsulated Chloride Ion in **1**

Cl(1)···N(18)	3.344	(Cl···H)	2.51
Cl(1)···N(38)	3.371	(Cl···H)	2.55
Cl(1)···C(32)	3.469	(Cl···H)	2.54
Cl(1)···C(15)	3.483	(Cl···H)	2.56
Cl(1)···C(40)	3.535	(Cl···H)	2.70
Cl(1)···C(20)	3.538	(Cl···H)	2.71

(b) Hydrogen Bonds Involving the Phosphate Anions in **11**

O(83)···N(153A)	2.81	O(92)···N(158B)	2.75
O(81)···N(168A)	2.57	O(88)···O(93)	2.60
O(82)···O(450)	2.78	O(87)···O(91)	2.49

(c) Hydrogen Bonds at the Lower Rim in the Calix[4]arenes in **11**

	molecule			molecule	
	A	B		A	B
O(150)···O(250)	2.84	3.00	O(350)···O(450)	2.92	2.91
O(250)···O(350)	2.99	2.96	O(450)···O(150)	3.00	2.76

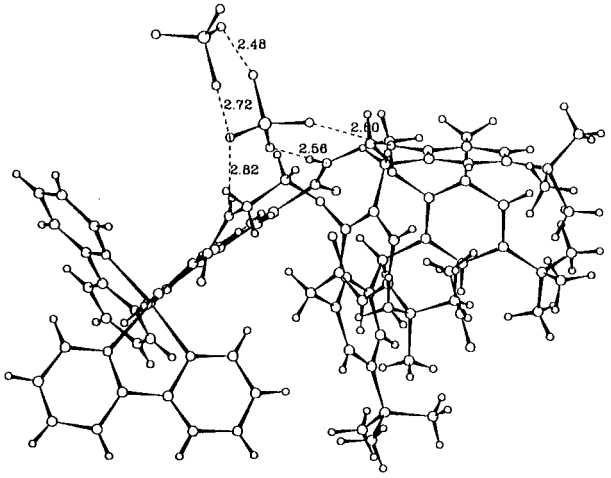


Figure 3. View of cation A with the associated dihydrogen phosphate ion. Hydrogen bonds are shown as dotted lines.

maintained with O···O distances of <3.0 Å. The positions of the hydrogen atoms of the −OH groups were not determined directly, and it may be that there is some disorder in their positions, as they can form bonds to either of the two adjacent ethereal oxygen atoms. The O···O distances are listed in Table 4. Of major interest in the structure is the interaction between the phosphate anions and the metal complex. While the positions of the phosphate ions relative to the cation are similar, the exact positions are radically different, as illustrated in Figures 3 and 4. It is interesting to note (and this is clear in both Figures 3 and 4) that the chain is folded well away from the initial direction in the C(16), O(150), C(36), O(350) plane. In the two molecules, the plane of the linked bipyridyl makes angles of 70.9, 56.3° with this plane. This tilt provides an open face toward which the phosphate anions can approach. The formation of hydrogen bonds is facilitated by the fact that the N−H groups are pointing away from the plane of the linking bipyridyl (rather than toward each other in the plane) and hence toward any approaching anions. This is caused by the C(bipy)−C(bipy)−C−N torsion angles being severely twisted from 0° (29.4, −42.3° in A; −21.1, 41.7° in B), presumably because of the repulsions between the N−H and the ortho C−H on the bipyridyl group.

We have investigated the conformation of **8** by molecular mechanics and molecular dynamics calculations using the Dreiding 2 force field within the CERIUS2 package.[23] Molecular dynamics calculations were carried out to investigate

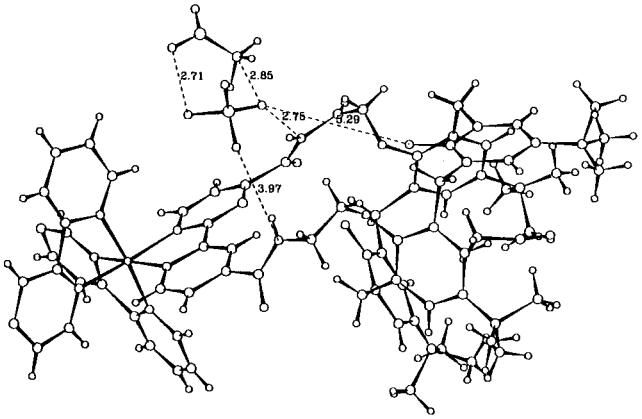


Figure 4. View of cation B with the associated dihydrogen phosphate ion. Hydrogen bonds are shown as dotted lines.

the likely conformations of the ligand. We found three possible low-energy conformations with the calix[4]arene in the partial cone conformation (172.2 kcal mol^{-1}), in the 1,3-alternate conformation (175.6 kcal mol^{-1}), and in the cone formation (195.5 kcal mol^{-1}). The 1,3-alternate conformation has a cylindrical shape,[23] and there is no way of including large anions. However, in both the cone and partial cone conformations, this is possible in a manner indicated by the crystal structure. During our molecular dynamics calculations, we found that the fold in the structure persisted in the cone formation and there was no indication that a straight-chain formation would be possible

For cation A, the phosphate forms three hydrogen bonds to the substituted calix[4]arene, two through the amide nitrogen atom and one directly to a separate O−H at the bottom rim of the cone. In addition, this phosphate also forms two strong hydrogen bonds to a second phosphate ion as is shown in Figure 3.[24] On the other hand, in cation B, the phosphate ion only forms one hydrogen bond via one of the amide nitrogen atoms. In B, the distances to the analogous atoms to which the hydrogen bonds are formed in A are 3.97 and 5.29 Å, clearly far too long for a hydrogen-bond interaction. This phosphate in B forms hydrogen bonds to a dimethyl sulfoxide solvent molecule. This molecule has only 50% occupancy, and the dimensions suggest that the oxygen atom may be disordered over the two positions which form hydrogen bonds. Details of these hydrogen bonds are given in Table 4.

It is difficult to be certain about the charge balance in this system. Clearly both cations are +2 charged. It seems likely that the two phosphate anions attached to the cation are equivalent. If they are −1, then the other unattached phosphate is −2, and if they are −2, then the other unattached phosphate is neutral. The former, with two $H_2PO_4^-$ and one HPO_4^{2-} anions seems the more likely description though there is no crystallographic evidence either for or against this view. We did consider whether either of the two dimethyl sulfoxide solvent molecules was indeed phosphate, but in neither solvent molecule could the fourth tetrahedral position be refined successfully.

There are large numbers of solvent molecules in the lattice although the majority are given only 50% occupancy. However, there is an acetonitrile solvent molecule in the cavity of each of the two calix[4]arenes. This is a well-known structural feature, and as is usually found, the methyl group is further

(23) Beer, P. D.; Drew, M. G. B.; Gale, P. A.; Leeson, P. B.; Ogden, M. I. *J. Chem. Soc., Dalton Trans.* **1994**, 3479.
(24) For other examples of $H_2PO_4^-$ dimerization in the solid state, see: Sessler, J. L.; Furuta, H.; Kral, V. *Supramol. Chem.* **1993**, *1*, 209 and ref 6.

Table 5. Stability Constant Data for **1**−**5**, **13**, and the Chloride and Dihydrogen Phosphate Anions in DMSO-d_6[a]

	K (M^{-1})			K (M^{-1})	
receptor	Cl^-	$H_2PO_4^-$	receptor	Cl^-	$H_2PO_4^-$
1	5.0×10^2	8.0×10^3	**4**	4.2×10^2	5.6×10^3
2	4.8×10^2	7.7×10^3	**5**	0.9×10^2	0.8×10^4
3	1.8×10^2	1.6×10^3	**13**	*b*	1.8×10^2

[a] Errors estimated to be ≤5%. [b] Extremely weak complex; a stability constant value could not be calculated.

down the cavity than the nitrogen atom presumably because of H···π interactions.

Solution Anion Coordination Investigations. (a) ^{1}H NMR Titrations. The recognition of anions in solution was initially studied by ^{1}H NMR spectroscopy. The addition of tetrabutylammonium chloride or dihydrogen phosphate to DMSO-d_6 ^{1}H NMR solutions of **1**−**5** resulted in remarkable perturbations of the respective receptor's protons. For example, with Cl^-, the amide protons of **1** and **5** shifted downfield by $\Delta\delta$ 1.0 and 1.2 ppm after addition of 1 equiv of anion. Also the 3,3′-bipyridyl protons of each receptor are substantially perturbed, suggesting the solution structure of the chloride anion complex is similar to that of the solid state complex of **1** described in the previous section.

In contrast, analogous ^{1}H NMR anion titrations with $[Ru(bipy)_3](PF_6)_2$ and $[Ru(bipy)_2L](PF_6)_2$ (L = 4,4′-bis(carboxyethyl)-2,2′-bipyridine) displayed *no* evidence of perturbation of any of the bipyridyl protons, a result which highlights the importance of the amide (CO−NH) group to the overall anion recognition process. The program EQNMR[25] was used to estimate the stability constants from the ^{1}H NMR titration data, and the results are summarized in Table 5. It is noteworthy that all the receptors exhibit a selectivity preference for $H_2PO_4^-$ over Cl^-, with the macrocyclic derivative **5** displaying the largest magnitude of selectivity difference.

Further evidence in support of the favorable anion hydrogen-bonding role of the amide group comes from comparing the stability constant data with those of a receptor that contains fewer amide groups, such as **13**. A dramatic ∼60-fold reduction in the magnitude of the stability constant for the $H_2PO_4^-$ anion occurs when one of the amide substituents of receptor **2** is absent, as with **13** (Table 5). Indeed, a similar significant reduction in the stability constant value is also observed with chloride (Table 5).

Molecular mechanics calculations using the universal force field within the CERIUS2 program were carried out on receptors **4** and **5** to investigate why chloride binding is relatively poor (Table 5). This cannot be due to any differences in nitrogen position, as the two nitrogen atoms in both receptors are approximately the same distance apart (6.51 Å) as they are in **5**, which does encapsulate chloride well.

The difference must be due to the fact that both **4** and **5** are cyclic molecules and the concomitant severe steric constraints limit the encapsulation of the chloride anion. Indeed for **5** the ring is so small that a stable conformation is unlikely with a trans amide group (energy 116.1 kcal mol^{-1}), while the energy with a cis amide group is much less (80.6 kcal mol^{-1}). Even so, there is no room within the cyclic cavity for a chloride anion, and molecular mechanics calculations showed no stable chloride anion included structures.

With receptor **4** however molecular mechanics calculations located a minimum-energy structure with the chloride anion significantly displaced from the ring. The two N−H groups are directed toward one side of the cavity so that they can form hydrogen bonds with the chloride anion. The energy of the complex was 76.8 kcal mol^{-1}, which reduced to 37.6 kcal mol^{-1} in the presence of chloride anion. This energy difference of 39.2 kcal mol^{-1} is significantly less than that observed in modelling receptor **1**, where the energy difference between **1** and (**1**)Cl^- is 73.8 kcal mol^{-1}.

(25) Hynes, M. J. *J. Chem. Soc., Dalton Trans.* **1993**, 311.

Table 6. Stability Constant Data for **11** and **12** with Various Anions in DMSO-d_6[a]

	K (M^{-1})		
receptor	Cl^-	Br^-	$H_2PO_4^-$
11	1.6×10^3	3.6×10^2	2.8×10^4
12	4.1×10^2	0.8×10^2	5.2×10^3

[a] Errors estimated to be ≤5%.

Table 7. Electrochemical Data[a]

	redox couples (V)			
		bipy reductions		
receptor	metal based $Ru^{II/III}$	+2/+1	+1/0	0/−1
1	1.10	−1.40	−1.78	−2.02
3	1.12	−1.44	−1.80	−2.01
4	1.01	−1.48	−1.84	−2.06
5	1.02	−1.56	−1.87	−2.07
11	1.12	−1.40	−1.80	−2.01

receptor	$\Delta E(H_2PO_4^-)$[b] (mV)	$\Delta E(HSO_4^-)$[b] (mV)	$\Delta E(Cl^-)$[b] (mV)	$\Delta E(Br^-)$[b] (mV)
1	*c*	*c*	40	30
3	130	15	65	60
4	175		70	10
5	150	20	65	
11	175	15	70	60

[a] Obtained in acetonitrile solution containing 0.1 mol dm^{-3} $[Bu_4N]PF_6$ as supporting electrolyte. Solutions were ca. 5×10^{-4} mol dm^{-3} in receptor, and potentials were determined with reference to an Ag^+/Ag electrode (330 ± 5mV vs SCE) at 21 ± 1 °C at 50 mV s^{-1} scan rate. [b] Cathodic shift perturbations of first ligand-centered reduction couple produced by presence of anions (up to 10 equiv) added as their tetrabutylammonium salts. [c] Precipitation of complex prevented a ΔE value from being determined.

Analogous ^{1}H NMR titration experiments were carried out with the calix[4]arene-containing receptors **11** and **12** with tetrabutylammonium chloride, bromide, and dihydrogen phosphate salts in DMSO-d_6. The stability constant values obtained from EQNMR titrimetric curve analysis are shown in Table 6. The selectivity trend $H_2PO_4^- > Cl^- > Br^-$ is shown by both receptors although **11**, containing the relatively smaller lower rim calix host cavity, exhibits the greater magnitude of selectivity preferences between all three anions.[26] It is also of note that a comparison of Tables 5 and 6 reveals for $H_2PO_4^-$ an increase in magnitude of stability constant in the order acyclic alkyl receptor **3** < macrocyclic receptors **4** and **5** < calix[4]arene receptor **11**.

(b) Electrochemical Anion Recognition Studies. Cyclic and square-wave voltammetry was used to investigate the electrochemical anion recognition properties of the receptors **1**, **3**, **4**, and **11** in acetonitrile, and the results are summarized in Table 7. With reference to the known electrochemical properties of $[Ru(bipy)_3][PF_6]_2$,[16] the respective reversible oxidation and reduction redox couples exhibited by the ruthenium(II) bipyridyl

(26) Although receptor **11** forms a 2:1 $H_2PO_4^-$: **11** stoichiometric complex in the solid state, in DMSO-d_6 solution EQNMR analysis of the ^{1}H and ^{31}P NMR titration curves gave no evidence for the existence of such a species in solution. Reinhoudt and co-workers have reported similar findings with their uranyl receptor systems; see ref 6.

Table 8. Electronic Absorption and Fluorescence Emission (in Bold) Data in DMSO for $[Ru(bipy)_3][PF_6]_2$, **7**, **13**, and **22**[a]

		λ_{max} (nm) ($10^{-4}\epsilon$ (dm^3 mol^{-1} cm^{-1}))		
		pure solvent	Cl^- [b]	$H_2PO_4^-$ [b]
$[Ru(bipy)_3][PF_6]_2$	$\pi-\pi^*(1)$	292 (9.87)	292 (10.9)	292 (*c*)
	MC	356 (0.39)	356 (0.39)	356 (*c*)
	MLCT	456 (1.92)	456 (1.95)	456 (*c*)
	MLCT	**607**	**607**	**607**
	Φ	0.062	0.062	
7	$\pi-\pi^*(1)$	292 (9.14)	292 (9.62)	292 (9.87)
	MC	354 (1.40)	354 (1.38)	354 (1.44)
	MLCT	462 (2.06)	462 (2.00)	462 (2.23)
	MLCT	**642**	**642**	**637**
	Φ	0.0163	0.0163	0.024
13	$\pi-\pi^*(1)$	292 (10.50)	292 (10.75)	292 (11.18)
	MC	358 (1.40)	358 (1.27)	358 (1.25)
	MLCT	470 (2.45)	470 (2.45)	470 (2.85)
	MLCT	**638**	**637**	**635**
	Φ	0.0184	0.0176	0.0184
22	$\pi-\pi^*(1)$	292 (12.01)	292 (12.65)	292 (12.25)
	MC	354 (1.74)	354 (1.76)	354 (1.57)
	MLCT	466 (2.44)	466 (2.45)	466 (2.54)
	MLCT	**640**	**638**	**622**
	Φ	0.0126	0.009 87	0.0360

[a] $\pi-\pi^*(2)$ absorption band below 280 nm cannot be resolved from solvent and chloride ion absorption. Solutions were 10^{-5} mol dm^{-3}. [b] Anions were added as tetrabutylammonium salts to 8×10^{-4} mol dm^{-3}. [c] Precipitation problems prevented ϵ data from being accurately determined.

receptors (Table 7) can be assigned to the metal-centered oxidation 1.01−1.12 V and the three bipyridyl ligand-centered reductions in the range −1.40 to −2.07 V. Because of the electron-withdrawing nature of the carbonyl amide moieties, the least cathodic bipyridyl ligand-centered reduction couple can be assigned to the amide-substituted bipyridyl group present in each receptor. Interestingly (Table 7), it is this redox couple that exclusively undergoes significant cathodic perturbations on addition of anionic guest species, suggesting, in agreement with solid state complex structures and ^1H NMR titration studies, that anion recognition takes place in the amide−bipyridyl vicinity of the respective receptor.[27]

Of particular relevance to the future design of amperometric chemical sensors were the novel results of electrochemical competition experiments with the calix[4]arene-containing receptor **11**. When a 5×10^{-4} M equimolar mixture of $H_2PO_4^-$, HSO_4^-, and Cl^- was added to an acetonitrile electrochemical solution of **11** (5×10^{-4} M), the bipyridyl-ligand-centered reduction couple shifted cathodically by an amount approximately the same ($\Delta E = 175$ mV) as that induced by the $H_2PO_4^-$ anion alone. The same result was even obtained when HSO_4^- and Cl^- anions were in 10-fold excess concentrations (5×10^{-3} M) over $H_2PO_4^-$ (5×10^{-4} M). This electrochemical anion competition result is in agreement with the receptor's Cl^- and $H_2PO_4^-$ stability constant values determined from ^1H NMR titration experiments (Table 6).

Electronic Absorption and Fluorescence Emission Spectra. Ruthenium(II) polypyridyl complexes exhibit metal-centered (MC), intraligand ($\pi-\pi^*$), and low-energy metal-to-ligand charge-transfer (MLCT) absorption bands.[16,28] Electronic absorption λ_{max} and ϵ data for **3**, **5**, and **11** in DMSO are summarized and contrasted with those of the prototype $[Ru(bipy)_3]^{2+}$ in Table 8. A minor difference in the spectra of the receptors compared to the prototype is that the respective MLCT band appears at a higher λ_{max} value. Disappointingly, the addition of excess amounts of chloride and dihydrogen phosphate anions resulted in no observable shifts of any of the λ_{max} absorption bands. However, significant increases in ϵ of the MLCT band of all three receptors were detectable with $H_2PO_4^-$ (Table 8).

Fluorescence emission spectroscopic measurements were also undertaken to probe anion binding. This highly sensitive technique earlier proved to be useful in the investigation of group 1 and 2 metal cation binding by crown ether-containing ruthenium(II) polypyridyl complexes.[29] In real sample analyses, interference from other fluorescent species are likely to be negligible due to the relatively high wavelength MLCT emission band of ruthenium(II) polypyridyl complexes.[16] As for the prototype, broad low-energy emission bands were observed for **3**, **5**, and **11**. Table 8 summarizes the data obtained in DMSO and with addition of Cl^- and $H_2PO_4^-$. The emission maxima are all bathochromically (red) shifted when compared to the prototype. All receptors display significant blue shifts in λ_{max} on addition of $H_2PO_4^-$, not observed with $[Ru(bipy)_3]^{2+}$, with **11** exhibiting the largest perturbation of 16 nm. These shifts are, in the case of **3** and **11**, accompanied by substantial increases in emission intensity (higher quantum yields). For example, Figure 5 shows the dramatic effect sequential amounts of $H_2PO_4^-$ has on the fluorescence emission spectrum of **11**. The higher quantum yields may be accounted for by considering the structures of receptors **3** and **11**. In their uncomplexed forms, the anion recognition sites in close proximity to the substituted bipyridyl group are free to move via rotation etc., and this lack of structural rigidity increases the chance of nonradiative decay. On complexation, the dihydrogen phosphate anion coordinates via hydrogen bonds to the amides (CO−NH) and, in the case of **11**, additionally to the calixarene hydroxyl group, with the effect of relatively restricting receptor mobility and rigidifying the supramolecular anion complex species. It is noteworthy that with the rigid macrocyclic receptor **5** the quantum yield does not change on $H_2PO_4^-$ complexation. The chloride anion induced much smaller fluorescence emission effects, with **3** proving to be insensitive and **5** and **11** displaying slight λ_{max} blue shifts and decreased quantum yields.[30]

Conclusions

The Lewis acidic redox-active and photoactive ruthenium(II) bipyridyl moiety in combination with ubiquitous amide CO−NH groups has been successfully incorporated into acyclic, macrocyclic, and calix[4]arene structural frameworks to produce novel receptors capable of the electrochemical and spectral recognition of anions.

The solid state structures of chloride and dihydrogen phosphate anion complexes of respectively **1** and **11** have been determined by X-ray analysis and highlight the importance of hydrogen bonding to the overall anion recognition process. Proton NMR titration investigations in deuterated DMSO solutions have shown these receptors form strong and, in the case of **5** and **11**, highly selective complexes with $H_2PO_4^-$. Electrochemical investigations have demonstrated that these receptors electrochemically recognize halide, HSO_4^-, and $H_2PO_4^-$ anions, with competition experiments suggesting **11** is a first generation prototype $H_2PO_4^-$-selective amperometric

(27) Analogous electrochemical anion recognition experiments with $[Ru(bipy)_3][PF_6]_2$ gave no evidence of anion complexation.
(28) Bryant, G. M.; Fergusson, J. E.; Powell, H. J. K. *Aust. J. Chem.* **1971**, *24*, 257.
(29) Beer, P. D.; Kocian, O.; Mortimer, R. J.; Ridgway, C. *J. Chem. Soc., Dalton Trans.* **1993**, 2629.
(30) Analogous fluorescence emission experiments in acetonitrile with Cl^- revealed substantial blue $\Delta\lambda_{max}$ shifts of up to 7 nm and increases in quantum yields.

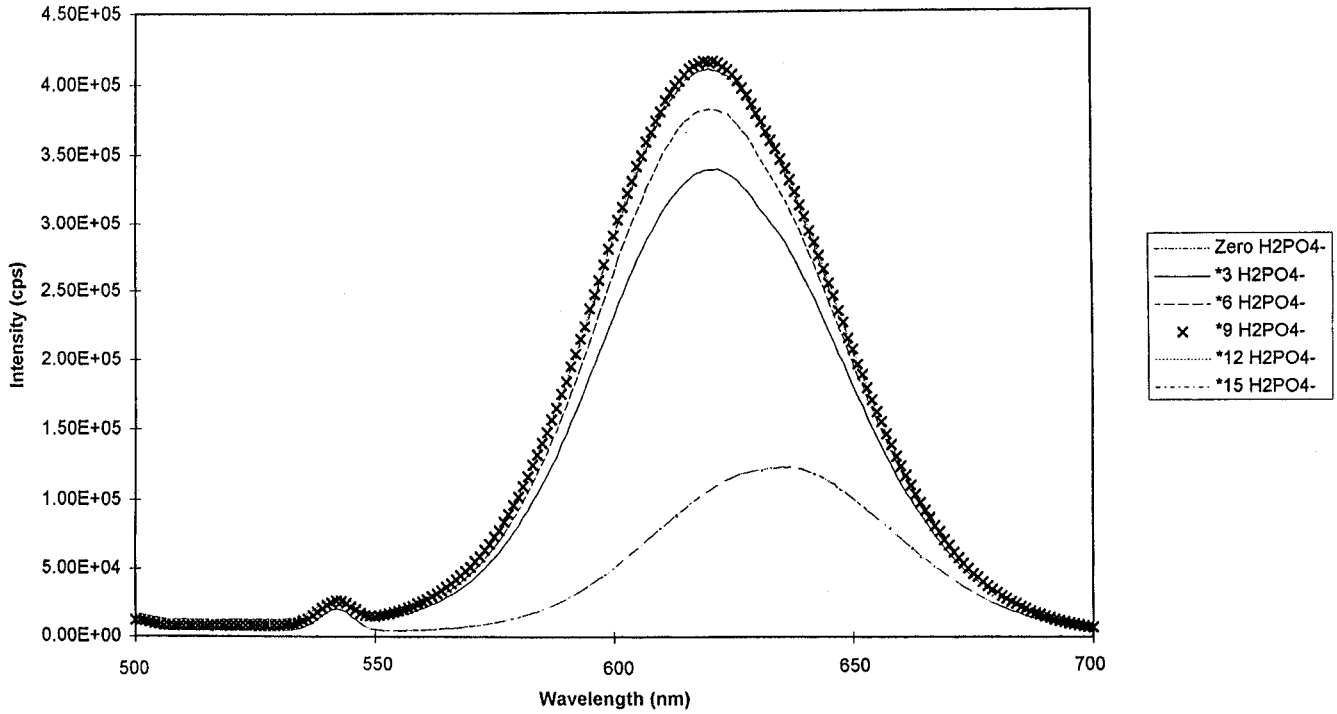


Figure 5. Effect of addition of stoichiometric amounts of $H_2PO_4^-$ on the fluorescence emission spectrum of **11** in DMSO.

sensor. Fluorescence emission spectral studies in DMSO revealed significant perturbations of **3**, **5**, and **11** receptors' MLCT λ_{max}, and with **3** and **11**, higher quantum yields result in the presence of $H_2PO_4^-$. Consequently, this novel class of anion receptor offers the dual capability of detecting and sensing anions via electrochemical *and* optical methodologies. The fabrication of this type of receptor into membranes, electronically conducting polymeric supports, and optical fibers will no doubt produce novel prototype molecular sensory devices of the future.

Experimental Section

Instrumentation. NMR spectra were obtained on a Bruker AM300 instrument using the solvent deuterium signal as internal reference. Fast atom bombardment (FAB) mass spectrometry was performed by the SERC Mass Spectrometry Service at University College, Swansea. Electrochemical measurements were carried out using an EG & G Princeton Applied Research 362 scanning potentiostat. A three-electrode system was employed with platinum-wire working electrodes and a platinum-mesh counter electrode. Electrode potentials were measured and are quoted with respect to an Ag/Ag^+ reference electrode (+0.330 V vs SCE) at 22 (±2) °C. No *iR* compensation was employed. Both counter and reference electrodes were each separated from the working electrode compartment of the electrochemical cell by glass frits. Measurements were carried out in deoxygenated acetonitrile solutions containing 0.1 M supporting electrolyte. A PC-controlled Hewlett-Packard HP 8452A diode-array spectrophotometer was employed for recording the electronic absorption spectra. Measurements were conducted on 10^{-5} M solutions of the complexes. A Perkin-Elmer Model 3000 fluorescence spectrophotometer was used for recording the fluorescence emission spectra. Measurements were conducted at 25 °C using a 1 × 1 cm rectangular quartz cuvette and deoxygenerated solutions. Data reported are for 10^{-5} M solutions. A Hewlett-Packard HP 8452A diode-array spectrophotometer was used for recording optical densities at each excitation maxima. Quantum yields (Φ) were calculated using the following equation:[31]

$$\frac{\text{fluorescence area 2}}{\text{fluorescence area 1}} = \left(\frac{\Phi_2}{\Phi_1}\right)\left(\frac{\text{optical density of 2}}{\text{optical density of 1}}\right)$$

For each sample measurement, $[Ru(bipy)_3](PF_6)_2$ in aerated water was used as standard ($\Phi = 0.028$).[32] The assumption is made that Φ will be independent of the anion of the salt; the chloride salt is used in this reference. This seems reasonable, as addition of chloride does not change Φ in DMSO.

Elemental analyses were performed at the Inorganic Chemistry Laboratory, University of Oxford. Melting points are uncorrected.

Solvent and Reagent Pretreatment. Where necessary, solvents were purified prior to use and stored under nitrogen. Dichloromethane and acetonitrile were distilled from CaH_2; diethyl ether was distilled from $LiAlH_4$. DMSO was dried over molecular sieves (4 Å) prior to use. Triethylamine and pyridine were dried over KOH. Benzene was distilled from Na. Column chromatography was performed with silica gel (Merck, particle size 0.0015−0.040 nm). All reactions were carried out in a nitrogen atmosphere. Unless stated to the contrary, commercial grade chemicals were used without further purification. 4,4′-Bis-(chlorocarbonyl)-2,2′-bipyridine,[18] 1,3-distal bis(cyanomethyl)calix[4]-arene (6),[22] and 4-methyl-2,2′-bipyridine[36] were synthesized according to literature procedures.

In the following NMR spectroscopic data Pyr indicates the substituted and Bpy the unsubstituted 2,2′-bipyridine nuclei.

4,4′-Bis((3,4-dimethoxyphenyl)carbamoyl)-2,2′-bipyridine. To a solution of 4-aminoveratrole (4 g, 26 mmol), triethylamine (1.80 g, 17 mmol), and 4-(dimethylamino)pyridine (0.01 g) in CH_2Cl_2 (100 mL) was added over 0.5 h a solution of 4,4′-bis(chlorocarbonyl)-2,2′-bipyridine (1.94 g, 8 mmol) in CH_2Cl_2 (50 mL). After stirring overnight at room temperature, the solvent was removed *in vacuo* and the residue suspended in chloroform (150 mL). This solution was washed with dilute acid and water, and the organic layer was filtered to produce a brown solid. Recrystallization from DMSO gave the ligand as off-white needles: yield 2.21 g (61%); mp >280 °C dec; ^{1}H NMR (CD_3CN) δ 10.57 (s, 2H, CONH), 8.95 (d, J = 5 Hz, Pyr 6,6′), 8.92 (s, 2H, Pyr 3,3′), 7.98 (dd, J = 5 and J = 1.4 Hz, 2H, Pyr 5,5′), 7.48 (d, J = 2.2 Hz, 2H, Ar), 7.40 (dd, J = 8.6 and J = 2.2 Hz, 2H, Ar), 6.97 (d, J = 8.6 Hz, 2H, Ar), 3.78 (s, 6H, OCH_3), 3.76 (s, 6H, OCH_3). Anal. Calcd for $C_{28}H_{26}N_4O_6$: C, 65.36; H, 5.09; N, 10.89. Found: C, 64.83; H, 5.11; N, 10.96.

4,4′-Bis((4-methoxyphenyl)carbamoyl)-2,2′-bipyridine. To a solution of *p*-anisidine (0.61 g, 5 mmol) and pyridine (0.47 g, 6 mmol) in CH_2Cl_2 (50 mL) was added over 0.5 h a solution of bipy bis(acid

(31) Parker, C. A.; Rees, W. T. *Analyst (London)* **1960**, *85*, 587.

(32) Nakamaru, K. *Bull. Chem. Soc. Jpn.* **1982**, *55*, 1639 and reference therein.

chloride) (0.55 g, 2 mmol) in CH_2Cl_2 (25 mL). The reaction mixture was then stirred at reflux for 5h and cooled to room temperature, and water (40 mL) was added. After 1 h of stirring the white crystalline bis(amide) was isolated, washed with water (20 mL), and recrystallized from a mixture of DMF (25 mL) and ethanol (10 mL): yield 0.71 g (78%); mp >342 °C dec; ^{1}H NMR (DMSO-d_6) δ 10.60 (s, 2H, CONH), 8.94 (d, J = 5 Hz, 2H, Pyr 6,6′), 8.9 (d, J = 1.6 Hz, 2H, Pyr 3,3′), 7.98 (dd, J = 5 and J = 1.6 Hz, 2H, Pyr 5,5′), 7.72 (d, J = 9 Hz, 4H, Ph 3,5), 6.97 (d, J = 9 Hz, Ph 2,6), 3.76 (s, 6H, OCH_3); ^{13}C NMR (DMSO-d_6) δ 163.4 (s, CONH), 155.9, 155.1 (2 × s, Pyr 2,2′and Ph 4), 150.1 (d, Pyr 6,6′), 143.5 (s, Pyr 4,4′), 131.6 (s, Ph 1), 122.3 (2 × d, Pyr 3,3′and Ph 3,5), 118.5 (d, Pyr 5,5′), 113.8, (d, Ph 2,6), 55.2 (q, OCH_3). Anal. Calcd for $C_{26}H_{22}N_4O_4$: C, 68.71; H, 4.88; N, 12.33. Found: C, 68.40; H, 4.86; N, 12.03.

4,4′-Bis((2-methoxyethyl)carbamoyl)-2,2′-bipyridine. To a solution of 2-methoxyethylamine (1.9 g, 22 mmol) in CH_2Cl_2 (60 mL) was added during 0.5 h a solution of bipy bis(acid chloride) (1.2 g, 4.3 mmol) in CH_2Cl_2 (60 mL). The reaction mixture was then stirred at reflux for 2 h and cooled to room temperature, and water (40 mL) was added. After 1 h of stirring, the white crystalline bis(amide) was isolated, washed with water (30 mL) and CH_2Cl_2 (30 mL), and dried. The organic layer from the filtrate was isolated, dried ($MgSO_4$), and evaporated to dryness. The crude product was recrystallized from ethanol: yield 1.26 g (82%); mp 217−219 °C; ^{1}H NMR (DMSO-d_6) δ 9.06 (br s, CONH), 8.89 (d, J = 5 Hz, 2H, Pyr 6,6′), 8.83 (s, 2H Pyr 3,3′), 7.89 (dd, J = 5 and J = 1.3 Hz, 2H, Pyr 5,5′), 3.40 (s, 4H, CH_2O), 3.30 (s, 4H, CH_2N); ^{13}C NMR (DMSO-d_6) δ 164.7 (s, CONH), 155.5 (s, Pyr 2,2′), 150.0 (d, Pyr 6,6′), 142.8 (s, Pyr 4,4′), 121.7 (d, Pyr 3,3′), 118.2 (d, Pyr 5,5′), 70.2 (t, CH_2O), 57.7 (q, OCH_3), 39.1 (t, CH_2N). Anal. Calcd for $C_{18}H_{22}N_4O_4$: C, 60,32; H, 6.19; N, 15.63. Found: C, 60.93; H, 6.07; N, 15.51.

First Macrocyclic Diamide. Solutions of 2,2′-(ethylenedioxy)-diethylamine (0.74 g, 5 mmol) in CH_2Cl_2 (65 mL) and of bipy bis(acid chloride) (1.4 g, 5 mmol) in CH_2Cl_2 (65 mL) were simultaneously added to a vigorously stirred solution of triethylamine (1.5 g, 15 mmol) in CH_2Cl_2 (400 mL) during 4 h at reflux, and the reaction mixture was refluxed for an additional 2 h. The pink solid phase was filtered off, the filtrate was washed with water (50 mL), and after drying and evaporation of the organic phase, the expected macrocyclic diamide was obtained as white powder. An analytical sample was crystallized from ethanol; yield 0.6 g (34%; mp >285 °C dec; ^{1}H NMR (DMSO-d_6) δ 8.86 (d, J = 4.9 Hz, 2H, Pyr 6,6′), 8.42 (s, 2H, Pyr 3,3′), 7.70 (d, J = 4.9 Hz, 2H, Pyr 5,5′), 3.70 (s, 4H, OCH_2CH_2O), 3.58 (t, 4H, OCH_2-CH_2N), 3,50 (t, 4H, OCH_2CH_2N); ^{13}C NMR (DMSO-d_6) δ 165.1 (s, CONH), 155.6 (s, Pyr 2,2′), 150.8 (d, Pyr 6,6′), 142.8 (s, Pyr 4,4′), 121.8, 121.6 (2 × d, Pyr 3,3′and Py 5,5′), 70.6 (t, OCH_2CH_2O), 69.1 (t, OCH_2CH_2N), 39.5 (t, NCH_2CH_2O); MS-FAB *m/z* 357 $[M + H]^+$, 379 $[M + Na]^+$.

Second Macrocyclic Diamide. Solutions of the bipy bis(acid chloride) (1.4 g, 5 mmol) in benzene (150 mL) and of 2,2-dimethyl-1,3-propanediamine (0.5 g, 5 mmol) in benzene (100 mL) were added simultaneously to a vigorously stirred solution of triethylamine (1.5 g, 15 mmol) in benzene (500 mL) at reflux, over a 3 h period, and the reaction mixture was refluxed for an additional 2 h. After cooling, the solid was filtered off, washed with ethanol (30 mL), and suspended in hot (60−65 °C) 20% ethanol (100 mL). After 0.5 h of stirring, the solid was isolated, washed with ethanol (30 mL), and dried: yield of the crude product which is a mixture of 1:1, 2:2, and 3:3 condensates was 1.5 g (96%); ^{1}H NMR (DMSO-d_6) δ 9.0 (br s, 2H, CONH), 8.9 (br s, 2H, Pyr 6,6′), 8.89 (s, 2H, Pyr 3,3′), 7.89 (br s, 2H Pyr 5,5′), 3.25 (br s, 4H, NCH_2C), 0.95 (br s, 6H, $C(CH_3)_2$). This was used in the next step without purification.

5,11,17,23-Tetrakis(1,1-dimethylethyl)-25,27-bis(2-aminoethoxy)-26,28-dihydroxycalix[4]arene (7). To a vigorously stirred solution of dinitrile **6** (4.7 g, 6.5 mmol) in diethyl ether (250 mL) was added portionwise a slurry of $LiAlH_4$ (2 g, 57 mmol), and the reaction mixture was refluxed for 5 h. After the reaction flask was immersed into an ice−water bath, the excess $LiAlH_4$ was destroyed by careful addition of wet benzene (150 mL) and water (10 mL). The clear organic layer was decanted, and the inorganic salts were rinsed with benzene (50 mL). The combined organic layers were evaporated to dryness to afford diamine **7** as a white solid which was pure enough to be used in the next step. An analytical sample was crystallized from petroleum ether (at −12 °C); yield of crude product 4.6 g (96%); mp 143−145 °C; ^{1}H NMR (CD_2Cl_2) δ 7.12 7.09 (2 × s, 4H each, Ar), 7.03 (s, 2H, OH), 4.35 (d, J = 12.8 Hz, 4H, ArCH_2Ar), 4.09 (t, J = 4.6 Hz, 4H, OCH_2), 3.43 (d, J = 12.8 Hz, 4H, ArCH_2Ar), 3.36 (t, J = 4.6 Hz, 4H, NCH_2), 1.26, 1.19 (s, 18H each, CH_3); ^{13}C NMR ($CDCl_3$) δ 150.2, 149.2 (2 × s, ArC−O), 147.5, 142.1 (2 × s, Ar ortho), 133.1, 127.6 (2 × s, Ar para) 125.8, 125.4 (2 × d, Ar meta), 78.5 (t, OCH_3), 42.4 (t, NCH_2), 34.1, 33.8 (2 × s, $C(CH_3)_3$), 32.1 (t, ArCH_2Ar), 31.6, 31.1 (2 × q, CH_3). Anal. Calcd for $C_{48}H_{66}N_2O_4$: C, 78.43; H, 9.05; N, 3.81. Found: C, 78.33; H, 9.00; N, 3.50.

Macrocyclic Diamide 8. Solutions of the bipy bis(acid chloride) (0.61 g, 2.17 mmol) and of bis(amine) **7** (1.6 g, 2.17 mmol) in equal volumes of benzene (100 mL) were added to a vigorously stirred and refluxing solution of triethylamine (0.6 g, 6 mmol) in benzene (600 mL) during 4 h. The reaction mixture was stirred and refluxed for additional 1 h and cooled to room temperature, water (50 mL) was added, and the mixture was stirred for another 1 h. A white microcrystalline product precipitated, which was isolated, washed with water and benzene, and dried; yield 0.37 g (18%): mp >282 °C (dec); ^{1}H NMR (CD_2Cl_2) δ 8.94 (t, 2H, CONH), 8.62 (d, J = 5 Hz, 2H, Pyr 6,6′), 8.79 (s, 2H, Pyr 3,3′), 7.85 (d, J = 5 Hz, 2H, Pyr 5,5′), 7.05, 6.83 (2 × s, 4H each, Ar meta), 6.90 (s, 2H, OH), 4.17 (d, J = 13.2 Hz, 4H, ArCH_2Ar), 4.16 (br s, 4H, OCH_2), 3.81 (br s, 4H, NCH_2), 3.34 (d, J = 13.2 Hz, 4H, ArCH_2Ar), 1.2, 0.98 (2 × s, 18H each); ^{13}C NMR ($CDCl_3$) δ 165.0 (s, CONH), 156.4 (s, Pyr 2,2′), 151.4 (d, Pyr 6,6′), 150.0, 149.6 (2 × s, ArC−O), 147.8, 142.7 (2 × s, Pyr 4,4′), 132.0, 127.6 (2 × s, Ar para), 126.1, 125.8 (2 × d, Ar, meta), 122.4 (d, Pyr 3,3′), 119.4 (d, Pyr 5,5′), 75.9 (t, OCH_2), 40.3 (t, NCH_2), 34.1, 33.9 (2 × s, $C(CH_3)_3$), 31.3 (ArCH_2Ar), 31.5, 30.9 (2 × q, CH_3); MS-FAB *m/z* 943 $[M]^+$, 966 $(M + Na]^+$.

5,11,17,23-Tetrakis(1,1-dimethylethyl)-25,27-bis(3-chloropropoxy)-26,28-dihydroxycalix[4]arene. To a suspension of *tert*-butylcalix[[4]-arene (12.2 g, 18.8 mmol) in acetonitrile (200 mL) were added K_2CO_3 (18 g, 130 mmol) and 3-chloropropyl tosylate (**17**) (10 g, 40.2 mmol), and this mixture was stirred at reflux for 36 h. The reaction mixture was cooled to room temperature, and the solid was collected by filtration and washed with methanol (50 mL). The white solid was suspended in water (150 mL), and after 0.5 h of stirring, the crude product was filtered off, washed with water (100 mL), and dried at 60 °C. This was dissolved in CH_2Cl_2 (55 mL), and the solution was filtered through Celite (3 g) which had been washed with CH_2Cl_2 (2 × 10 mL). The filtrate was concentrated to 50 mL, and with stirring, methanol (300 mL) was slowly added. After crystallization at room temperature (2 h) and at 5 °C (3 h), the crystalline product obtained was filtered off and washed with methanol (100 mL); yield 10.5 g (70%); mp >300 °C (dec); ^{1}H NMR (CD_2Cl_2) δ 8.22 (s, 2H, OH), 7.07, 7.05 (2 × s, 4H each, Ar), 4.27 (d, J = 13.0 Hz, 4H, ArCH_2Ar), 4.23 (t, J = 6.3 Hz, 4H, OCH_2), 4.14 (t, J = 5.6 Hz, 4H, CH_2Cl), 3.39 (d, J = 13.0 Hz, 4H, ArCH), 2.48 (m, 4H, $CH_2CH_2CH_2$), 1.23, 1.15 (2 × s, 18H each, CH_3); ^{13}C NMR (CD_2Cl_2) δ 150.8, 149.2 (2 × s, ArC−O), 148.0, 142.2 (2 × s, Ar ortho), 133.0, 127.1 (2 × s, Ar para), 126.3, 125.8 (2 × d, Ar meta), 72.7 (t, OCH_2), 42.0 (t, CH_2Cl), 34.3, 33.8 (2 × s, $C(CH_3)_3$), 33.5 (t, $CH_2CH_2CH_2$), 32.1 (ArCH_2Ar), 31.5, 31.1 (2 × q, CH_3). Anal. Calcd for $C_{50}H_{66}O_4Cl_2$: C, 74.88; H, 8.29; Cl, 8.84. Found: C, 74.72; H, 8.35; Cl, 9.02.

5,11,17,23-Tetrakis(1,1-dimethylethyl)-25,27-bis(3-azidopropoxy)-2,6,28-dihydroxycalix[4]arene. A mixture of the bis(chloro) calix-[4]arene compound (4.4 g, 5.5 mmol) and sodium azide (1.43 g, 2.2 mmol) in dimethylformamide (80 mL) was stirred at 70−75 °C for 24 h. The reaction mixture was poured into cold water (350 mL), and the resultant mixture was stirred at room temperature for 1 h. The microcrystalline material obtained was filtered off, washed with water (2 × 50 mL), and dried over P_2O_5 *in vacuo*: yield of the crude product 4.5 g, 100%. This was dissolved in chloroform (30 mL), and the solution was filtered through Celite (1 g) which had been washed with two portions of chloroform (2 × 5 mL). The filtrate was concentrated to 30 mL, and under stirring, methanol (150 mL) was slowly added. A white suspension formed, which was left to stand overnight at 0 to −5 °C. The crystalline product obtained was filtered off, washed with methanol (50 mL), and dried *in vacuo*: yield 4.1 g (92%); mp 226−228 °C; ^{1}H NMR ($CDCl_3$) δ 7.57 (s, 2H, OH), 7.06 (s, 4H, Ar), 6.86

(s, 4H, Ar), 4.22 (d, J = 13 Hz, $ArCH_2Ar$), 4.06 (t, J = 5.7 Hz, 4H, OCH_2), 3.89 (t, J = 6.7 Hz, 4H, CH_2N_3), 3.34 (d, J = 13 Hz, $ArCH_2$-Ar), 2.25 (m, J = 6.2 Hz, 4H, $CH_2CH_2CH_2$); mp 226−228 °C; ^{13}C NMR ($CDCl_3$) δ 150.6, 149.3 (2 × s, ArC−O), 147.2, 141.7 (2 × s, Ar ortho), 132.6, 127.6 (2 × s, Ar para), 125.6, 125.1 (2 × d, Ar meta), 72.6 (t, OCH_2), 48.3 (t, CH_2N_3), 34.0, 33.8 (2 × s, $C(CH_3)_3$), 31.7, 29.6 (2 × t, $ArCH_2Ar$ and $CH_2CH_2CH_2$), 31.7, 31.0 (2 × q, CH_3). Anal. Calcd for $C_{50}H_{66}N_6O_4$: C, 73.68; H, 8.16; N, 10.31. Found: C, 73.41; H, 8.06; N, 10.02.

5,11,17,23-Tetrakis(1,1-dimethylethyl)-25,27-bis(3-aminopropoxy)-26,28-dihydroxycalix[4]arene (9). To a solution of the bis(azide) (3 g, 3.7 mmol) in a mixture of THF (40 mL) and MeOH (40 mL), were added 5% Pd/C (1 g) catalyst and hydrogen at 35−40 °C and atmospheric pressure (3.5 h). The catalyst was removed and washed with methanol, the solvent was evaporated, the crude product was redissolved in CH_2Cl_2, and the solution was loaded onto an alumina column prepared in CH_2Cl_2. The impurities were eluted with a mixture of CH_2Cl_2−MeOH (20:1), and the product with the same mixture was saturated with ammonia. Evaporation of the solvent afforded **9** as white powder: yield 2.2 g (78%); ^{1}H NMR ($CDCl_3$) δ 7.63 (br s, 2H, OH), 7.06 (s, 4H, Ar), 4.26 (d, J = 13 Hz, 4H, $ArCH_2Ar$), 4.07 (t, J = 5.8 Hz, 4H, OCH_2), 3.33 (d, J = 13 Hz, 4H, $ArCH_2Ar$), 3.2 (t, J = 6.6 Hz, 4H, NCH_2), 2.13 (m, J = 6.2 Hz, 4H, $CH_2CH_2CH_2$), 1.81 (br s, 4H, NH_2, 1.3, 0.98 (2 × s, 18H each, CH_3); ^{13}C NMR ($CDCl_3$) δ 150.7, 149.8 (2 × s, ArC−O), 146.9, 141.5 (2 × s, Ar ortho), 132.6, 127.9 (2 × s, Ar para), 125.5, 125 (2 × d, Ar meta), 74.9 (t, OCH_2), 39.8, 33.8 (2 × s, $C(CH_3)_3$), 33.9, 31.7 (2 × t, $ArCH_2Ar$ and $CH_2CH_2CH_2$), 31.7, 31 (2 × q, CH_3). An analytical sample of bis(amine) dihydrochloride **9** was prepared by introducing dry HCl into a vigorously stirred solution of bis(amine) **9** (0.5 g, 0.65 mmol) in CH_2Cl_2 (20 mL); yield of fine white powder 0.54 g (100%); mp >285 °C dec. Anal. Calcd for $C_{50}H_{72}Cl_2N_2O_4$: C, 71.83; H, 8.68; N, 3.35; Cl, 7.52. Found: C, 72.06; H, 8.63; N, 3.51; Cl, 7.52.

Macrocyclic Diamide 10. Solutions of the bipy bis(acid chloride) (0.73 g, 2.6 mmol) and bis(amine) (9) (2 g, 2.6 mmol) in equal volumes of benzene (150 mL) were added simultaneously to a solution of vigorously stirred and refluxing benzene (500 mL) containing triethylamine (0.73 g, 7.2 mmol), over a 4 h period, whereupon refluxing was continued for a further 2 h. After cooling, the solid was filtered off and the filtrate was concentrated *in vacuo*. The residue was dissolved in CH_2Cl_2 (50 mL), washed with water (50 mL), dried ($MgSO_4$), and purified by silica gel chromatography (eluent: CH_2Cl_2, CH_2Cl_2 −5% *i*-PrOH) to give a sample of **10**. Crystallization performed by adding MeOH (4 mL) to a CH_2Cl_2 (1 mL) solution of diamide afforded a white crystalline material; yield 0.2 g (8%); mp >285 °C (dec); ^{1}H NMR ($CDCl_3$) δ 8.97 (d, J = 5 Hz, 2H, Pyr 5,5′), 8.22 (s, 2H, Pyr 3,3′), 8.04 (t, J = 10 Hz, 2H, CONH), 7.88 (dd, J = 5 and J = 1 Hz, 2H, Pyr 5,5′), 7.12 (s, 4H, Ar), 6.71 (s, 4H, Ar), 6.58 (s, 2H, OH), 4.20−4.25 (m, 8H, $ArCH_2Ar$ and OCH_2), 3.89 (m, 4H, $CONHCH_2$), 3.4 (d, J = 13.4 Hz, 4H, $ArCH_2Ar$), 2.23 (m, $CH_2CH_2CH_2$), 1.32, 0.88 (s, 18H each, CH_3); ^{13}C NMR ($CDCl_3$) δ 165.6 (s, CONH), 155.6 (s, Pyr 2,2′), 151.5 (d, Pyr 6,6′), 150.0, 149.4 (2 × s, Ar -O), 147.2, 142.9 (2 × s, Ar ortho), 142.4 (s, Pyr 4,4′), 132.0, 128.1 (2 × s, Ar para), 125.7 125.4 (2 × d, Ar meta), 122.2 (d, Pyr 3,3′), 119.0 (d, Pyr 5,5′), 73.5 (t, OCH_2), 36.6 (t, NCH_2), 33.9 (s, $C(CH_3)_3$), 31.7, 29.7 (t, $ArCH_2Ar$ and $CH_2CH_2CH_2$), 31.7, 30.9 (2 × q, CH_3); MS-FAB *m/z* 972 $[M + H]^+$, 993 $[M + Na]^+$.

2,2′-Bipyridine-4-carboxylic Acid. A mixture of 4-methyl-2,2′-bipyridine (2 g, 11.7 mmol) and selenium(IV) dioxide (2.8 g, 25 mmol) in diglyme (30 mL) was stirred at 125−135 °C for 4 h; then water (40 mL) was added and the reduced selenium metal isolated by filtration through a Celite bed. The solid was washed with hot water (30 mL). To the vigorously stirred yellow filtrate was added a saturated solution of $KMnO_4$ (2 g, 12.6 mmol), and the mixture was stirred at room temperature for 3 h and then at 70 °C for 1 h. The inorganic solid (MnO_2) was removed by filtration through a Celite bed and washed with alkaline water (1 g KOH in 35 mL), and the yellow filtrate was evaporated to dryness. The solid residue was dissolved in water (60 mL), and the solution was stirred with charcoal (1 g) and filtered through Celite. The pure acid was precipitated from the filtrate by adjusting the pH to 3−4 with 10% HCl. The pale yellow microcrystalline product was isolated, washed with water (30 mL), and dried at 60 °C; yield 1.35 g (57.6%); mp 242−243 °C; ^{1}H NMR (DMSO-d_6) δ 8.86 (d, J = 4.8 Hz, 1H, Pyr 6), 8.80 (br s, 1H, Pyr 3), 8.72 (d, J = 4.8 Hz, 1H, Pyr 6′), 8.41 (d, J = 7.8 Hz, 1H, Pyr 3′), 7.97 (dt, J = 7.8 and J = 1.5 Hz, 1H, Pyr 4′), 7.86 (d, J = 4.8 Hz, 1H, Pyr 5), 7.50 (ddd, J = 7.8, J = 4.8 and 1.5 Hz, Pyr 5′); ^{13}C NMR (DMSO-d_6) δ 166.2 (s, COOH), 156.3, 154.4 (2 × s, Pyr −2,2′), 150.3, 149.4 (2 × d, Pyr 6,6′), 139.6 (s, Pyr 4), 137.4 (d, Pyr 4′), 124.6, 123.0 (2 × d, Pyr 5,5′), 120.6, 119.5 (2 × d, Pyr 3,3′). Anal. Calcd for $C_{11}H_8N_2O_2$: C, 66.00; H, 4.03; N, 13.99. Found: C, 66.47; H, 3.66; N, 14.09.

4-((4-Methoxyphenyl)carbamoyl)-2,2′-bipyridine. The vacuum-dried acid chloride (5 mmol), prepared from the monoacid (1.0 g, 5 mmol) and thionyl chloride (15 mL) by stirring at 70 °C for 3 h and removing the excess thionyl chloride, was dissolved in CH_2Cl_2 (35 mL) in the presence of pyridine (1.2 g, 15 mmol), and a slurry of *p*-anisidine (0.67 g, 5.5 mmol) was added. The reaction mixture was stirred at room temperature for 0.5 h and refluxed for 2 h. The mixture then was diluted with CH_2Cl_2 (40 mL) and washed successively with water (40 mL) and a saturated solution of $NaHCO_3$ (30 mL). The organic layer after drying ($MgSO_4$) and removing the solvent afforded a brown solid, which was crystallized from ethanol (50 mL) to give the product as off-white fine needles; yield 1.3 g (86%); mp 190 °C; ^{1}H NMR (DMSO-d_6) δ 10.56 (s, 1H, CONH), 8.87 (d, J = 4.8 Hz, Pyr 6), 8.86 (s, 1H, Pyr 3), 8.75 (dd, J = 4.8 and J = 0.8 Hz, 1H, Pyr 6′), 8.44 (d, J = 7.9 Hz, 1H, Pyr 3′), 7.98 (dt, J = 4.8 and J = 1.6 Hz, 1H, Pyr 4′), 7.92 (dd, J = 4.8 and J = 0.8 Hz, 1H, Pyr 5), 7.72 (d, J = 9 Hz, 2H, Ph 2,6), 7.49 (ddd, J = 4.9 and J = 0.8 Hz, 1H, Pyr 5′), 6.95 (d, J = 9 Hz, 2H, Ph 3,5), 3.76 (s, 3H, $PhOCH_3$); ^{13}C NMR (DMSO-d_6) δ 163.5 (s, CONH), 156.0, 155.9, 154.7 (3 × s, Pyr 2,2′ and Ph 4), 149.9, 149.4 (2 × d, Pyr 6,6′), 143.3 (s, Pyr 4), 137.4 (d, Pyr 4′), 131.7 (s, Ph 1), 124.5, 121.8 (2 × d, Pyr 5,5′), 122.9 (d, Ph 3,5), 120.7, 118.3 (2 × d, Pyr 3,3′), 113.8 (d, Ph 2,6), 55.2 (q, $PhOCH_3$). Anal. Calcd for $C_{17}H_{15}N_3O_2$: C, 70.81; H, 4.95; N, 13.76. Found: C, 71.22; H, 4.91; N, 14.00.

General Procedure for the Preparation of Ruthenium(II) Bipyridyl Receptors. An equimolar mixture of $[RuCl_2(bipy)_2]\cdot 2H_2O$ and the appropriate 4,4′-diamide-substituted bipyridine ligand was suspended in a particular solvent mixture, and the suspension was refluxed for typically 12 h. The solvent was removed in vacuo to leave a dark red crude product, which was purified by column chromatography on Sephadex LH 20 using acetonitrile and acetonitrile−ethanol (10:1) solvent mixtures. After removal of the solvent in vacuo, the product was dissolved in water and addition of an excess amount of an aqueous solution of NH_4PF_6 produced an orange precipitate, which was washed with water and dried *in vacuo* over P_2O_5.

(a) [4,4′-Bis((3,4-dimethoxylphenyl)carbamoyl)-2,2′-bipyridine]-bis(2,2′-bipyridine)ruthenium(II) bis(hexafluorophosphate) dihydrate (1) was prepared from the corresponding bis(amide) (260 mg, 0.5 mmol) and $[RuCl_2(bipy)_2]\cdot 2H_2O$ (260 mg, 0.5 mmol) in DMF (20 mL); yield 350 mg (57%); ^{1}H NMR (MeCN-d_3) δ 9.41 (s, 2H, N−H), 9.39 (s, 2H, Pyr 3,3′), 8.53 (d, J = 8.2 Hz, 4H, Bpy 3,3′), 8.08 (m, 4H, Bpy 4,4′), 7.94 (d, J = 5.9 Hz, 2H, Pyr 6,6′), 7.86 (dd, J = 5.9 and 1.6 Hz, Pyr 5,5′), 7.75 (t, J = 5.9 Hz, 4H, Bpy 3,3′), 7.51 (d, J = 2.3 Hz, 2H, Ar), 7.45 (m, 4H, Bpy 5,5′), 7.36 (dd, J = 8.7 and 2.4 Hz, 2H, Ar), 6.90 (d, J = 8.7 Hz, 2H, Ar), 3.78 (s, 6H, OCH_3), 3.76 (s, 6H, OCH_3). Anal. Calcd for $C_{48}H_{42}F_{12}N_8O_6P_2Ru$: C, 46.64; H, 3.59; N, 9.07. Found: C, 46.58; H, 3.50; N, 9.34.

(b) [4,4′-Bis((4-methoxyphenyl)carbamoyl)-2,2′-bipyridine]bis-(2,2′-bipyridine)ruthenium(II) bis(hexafluorophosphate) dihydrate (2) was prepared from the corresponding bis(amide) (230 mg, 0.5 mmol) and $[RuCl_2(bipy)_2]\cdot 2H_2O$ (300 mg, 0.57 mmol) in a mixture of EtOH (20 mL)−H_2O (5 mL)−AcOH (5 mL): yield 500 mg (85%); ^{1}H NMR (MeCN-d_3) δ 9.15 (br s, 2H, Pyr 3,3′), 9.13 (br s, 2H, CONH), 8.54 (d, J = 8 Hz, 4H, Bpy 3,3′), 8.08 (m, 4H, Bpy 4,4′), 7.96 (d, J = 5.8 Hz, 2H, Pyr 6,6′), 7.84 (dd, J = 5.8 and J = 1.6 Hz, 2H, Pyr 5,5′), 7.75 (d, J = 5.5 Hz, 4H, Bpy 3,3′), 7.67 (d, J = 9 Hz, 4 H, Ph 2,6), 7.42 (m, 4H, Bpy 5,5′), 6.94 (d, J = 9 Hz, 4H, Ph 3,5), 3.75 (s, 6H, OCH_3); ^{13}C NMR (MeCN-d_3) δ 162.4 (s, CONH), 158.4, 157.9, 157.8, 157.6 (4 × s, Pyr 2,2′, Bpy 2,2′ and Ph 4), 153.4 (d, Pyr 6,6′), 152.6, 152.2 (2 × d, Bpy 6,6′), 143.9 (s, Pyr 4,4′), 139.1 (d, Bpy 4,4′), 131.7 (s, Ph 1), 128.7 (d, Bpy 5,5′), 126.2 (d, Pyr 5,5′), 125.3 (d, Bpy 3,3′), 123.5 (d, Ph 3,5), 123.1 (d, Pyr 5,5′), 114.9 (d, Ph 2,6), 56.0 (q, $PhOCH_3$). Anal. Calcd for $C_{46}H_{42}F_{12}N_8O_6P_2Ru$: C, 46.28; H, 3.55; N, 9.39. Found: C, 46.65; H, 3.32; N, 9.28.

(c) [4,4′-Bis((2-methoxyethyl)carbamoyl)-2,2′-bipyridine]bis(2,2′-bipyridine)ruthenium(II) bis(hexafluorophosphate) dihydrate (3) was prepared from the corresponding bis(amide) (178 mg, 0.5 mmol) and $[RuCl_2(bipy)_2]\cdot 2H_2O$ (312 mg, 0.6 mmol) in 90% ethanol (30 mL); yield 490 mg (90%); ^{1}H NMR (MeCN-d_3) δ 8.91 (d, J = 1.5 Hz, 2H, Pyr 3,3′), 8.53 (d, J = 8.2 Hz, 4H, Bpy 3,3′), 8.08 (m, 4H, Bpy 4,4′), 7.89 (d, J = 5.8 Hz, 2H, Pyr 6,6′), 7.33−7.64 (m, 6H, Pyr 5,5′and Bpy 6,6′), 7.41 (m, 4H, Bpy 5,5′), 3.56 (m, 10H, CH_2OCH_3), 3.32 (s, 4H, NCH_2); ^{13}C NMR (MeCN-d_3) δ 164.1 (s, CONH), 158.7, 157.9 (2 × s, Bpy and Pyr 2,2′), 153.5 (s, Pyr 6,6′), 152.7 (d, Bpy 6,6′), 143.7 (s, Pyr 4,4′), 139.5 (d, Bpy 4,4′), 128.6 (d, Bpy 3,3′), 125.8 (d, Pyr 3,3′), 125.3 (d, Bpy 5,5′), 123.0 (d, Pyr 5,5′), 71.1 (t, OCH_2), 58.7 (q, OCH_3), 40.7 (t, NCH_2). Anal. Calcd for $C_{38}H_{42}F_{12}N_8O_6P_2Ru$: C, 41.58; H, 3.86; N, 10.21. Found: C, 41.38; H, 3.48; N, 10.28.

(d) Ruthenium(II) macrocyclic receptor 4 was prepared from the corresponding macrocyclic bipy ligand (170 mg, 0.5 mmol) and $[RuCl_2(bipy)_2]\cdot 2H_2O$ (300 mg, 0.6 mmol) in a mixture of EtOH (10 mL)−H_2O (10 mL)−AcOH (2 mL); yield 450 mg (87%); ^{1}H NMR (MeCN-d_3) δ 9.25 (d, J = 1.8 Hz, 2H, Pyr 3,3′), 8.52 (dd, J = 8 and J = 2.8 Hz, 4H, Bpy 3,3′), 8.08 (m, 4H, Bpy 4,4′), 7.81 (d, J = 5.7 Hz, 2H, Pyr 6,6′), 7.74 (d, J = 6.1 Hz, 4H, Bpy 6,6′), 7.71 (dd, J = 5.7 and J = 1.8 Hz, 2H, Pyr 5,5′), 7.65 (br s, 2H, CONH) 7.41 (m, 4H, Bpy 5,5′), 3.72 (s, 4H, OCH_2CH_2O), 3.62 (br s, 4H, OCH2CH2N), 3.48 (br s, 4H, OCH_2CH_2N); ^{13}C NMR (MeCN-d_3) δ 164.0 (s, CONH), 157.8, 157.8, 157.8 (2 × s, Bpy and Pyr 2,2′), 153.6 (d, Pyr 6,6′), 152.8 (d, Bpy 6,6′), 143.3 (s, Pyr 4,4′), 139.0 (d, Bpy 4,4′), 128.6 (d, Bpy 3,3′), 126.3 (d, Pyr 3,3′), 125.2 (d, Bpy 5,5′), 123.6 (d, Pyr 5,5′), 72.3 (t, OCH_2CH_2O), 70.1 (t, OCH_2CH_2O), 41.0 (NCH_2CH_2O). Anal. Calcd for $C_{38}H_{40}F_{12}N_8O_6P_{12}Ru$: C, 41.65; H, 3.68; N, 10.23. Found: C, 41.30; H, 3.65; N, 9.83.

(e) Ruthenium(II) macrocyclic receptor 5 was prepared from the corresponding macrocyclic bipy ligand (2 g, 5.7 mmol) and $[RuCl_2(bipy)_2]\cdot 2H_2O$ (3.1 g, 6 mmol) in a 1:1:1 mixture of EtOH, H_2O, and AcOH (60 mL); yield 0.5 g (80%); ^{1}H NMR (MeCN-d_3) δ 9.10 (s, 2H, Pyr 3,3′), 8.53 (d, J = 8.2 Hz, 4H, Bpy 3,3′), 8.23 (br s, 2H, CONH), 8.07 (m, 4H, Bpy 4,4′), 7.94 (d, J = 5.9 Hz, 2H, Pyr 6,6′), 7.79 (d, J = 5.9 Hz, 2H, Pyr 5,5′), 7.72 (m, 4H, Bpy 6,6′), 7.42 (m, 4H, Bpy 5,5′), 3.35 (br s, 4H, NCH_2C), 1.00 (br s, 6H, CH_3); ^{13}C NMR (MeCN-d_3) δ 165.4 (s, CONH), 158.4, 157.7, 157.6 (3 × s, Pyr and Bpy 2,2′), 153.4 (d, Pyr 6,6′), 152.6, 152.5 (2 × d, Bpy 6,6′), 143.5 (s, Pyr 4,4′), 139.1 (d, Bpy 4,4′), 128.6 (d, Pyr 3,3′), 126.5 (d, Pyr 3,3′), 125.3 (d, Bpy 5,5′), 122.4 (d, Pyr 5,5′), 46.5 (t, NCH_2), 38.0 (s, $C$$CH_3$), 24.1 (q, CH_3); MS-FAB *m/z* 724 $[M - 2PF_6^- - 2H_2O]^+$, 1050 $[M]^+$. Anal. Calcd for $C_{37}H_{38}N_8O_4P_2F_{12}Ru$: C, 42.33; H, 3.65; N, 10.67. Found: C, 42.02; H, 3.42; N, 10.65.

(f) [4-((4-Methoxyphenyl)carbamoyl)-2,2′-bipyridine]bis(2,2′-bipyridine) ruthenium(II) bis(hexafluorophosphate) dihydrate (13) was prepared from the corresponding bipy amide (122 mg, 0.4 mmol) and $[RuCl_2(bpy)_2]\cdot 2H_2O$ (210 mg, 0.4 mmol) in a mixture of EtOH (10 mL)−AcOH (0.2 mL): yield 375 mg (90%) ^{1}H NMR (MeCN-d_3) δ 8.98 (s, 1H, CONH), 8.86 (s, 1H, Pyr 3), 8.64 (d, J = 8.3 Hz, 1H, Pyr 3′), 8.50 (d, J = 8.3 Hz, 4H, Bpy 3,3′), 8.11−8.04 (m, 5H, Pyr 4′ and Bpy 4,4′), 7.90 (d, J = 5.9 Hz, 1H, Pyr 6), 7.76−7.72 (m, 6H, Pyr 5, Pyr 6′, and Bpy 6,6′), 7.62 (d, J = 8.5 Hz, 2H, Ph 2,6), 7.45−7.38 (m, 5H, Pyr 5′ and Bpy 5,5′), 6.96 (d, J = 8.5 Hz, 2H, Ph 3,5), 3.79 (s, 3H, PhOCH_3); ^{13}C NMR (MeCN-d_3) δ 162.8 (s, CONH), 157.4 (3 × s, Bpy 2,2′ and Pyr 2,2′), 152.8, 152.2, 152.1 (3 × d, Bpy 6,6′ and Pyr 6,6′), 152.2 (s, Ph 4), 143.5 (s, Pyr 4), 138.5, 138.4 (2 × d, Pyr 4′ and Bpy 4,4′), 131.3 (s, Ph 1), 128.4, 128.1 (2 × d, Pyr 5′ and Bpy 5,5′), 125.0, 124.7 (3 × d, Pyr 5, Pyr 3′ and Bpy 3,3′), 122.9 (d, Ph 2,6), 122.3 (d, Pyr 3), 114.5 (d, Ph 3,5), 55.6 (q, PhOCH_3). Anal. Calcd for $C_{38}H_{35}N_7O_4F_{12}P_2Ru$: C, 43.69; H, 3.38; N, 9.38; Ru, 9.67. Found: C, 43.96; H, 3.02; N, 9.39; Ru, 9.37.

(g) Ruthenium(II) calix[4]arene receptor 11 was prepared from **8** (110 mg, 0.117 mmol) and $[RuCl_2(bipy)_2]\cdot 2H_2O$ (80 mg, 0.154 mmol) in a mixture of EtOH (9 mL)−H_2O (1 mL)−AcOH (1 mL). A solution of the product dissolved in CH_2Cl_2 (40 mL) was vigorously stirred with a solution of NH_4PF_6 (1.2 g) in water (15 mL) for 0.5 h. After separation and drying ($MgSO_4$), the organic phase was evaporated and the resulting solid was dried *in vacuo* at 50−60 °C to afford **11** as dark-red solid; yield 110 mg (76%); ^{1}H NMR (CD_2Cl_2) δ 9.30 (s, 2H, Pyr 3,3′), 8.43 (m, 4H, Bpy 3,3′), 8.12 (br s, 2H, CONH), 8.42 (m, 4H, Bpy 4,4′), 7.85 (d, J = 5.7 Hz, 2H, Pyr 5,5′), 7.73 (d, J = 5.7 Hz, 2H, Pyr 6,6′), 7.70 (2 × d, 4H, Bpy 6,6′), 7.46 (m, 4H, Bpy 5,5′), 7.42 (s, 2H, OH), 7.04, 7.02 (2 × s, 2H each, Ar 10, 24 and Ar 12, 22), 6.96 (s, 4H, Ar 4, 6, 16, 18), 4.36 (m, 8H, OCH_2 and $ArCH_2Ar$), 3.75 (m, 4H, NCH_2), 3.37, 3.32 (2 × d, J = 12.9 Hz, 2H each, $ArCH_2Ar$), 1.22, 1.06 (2 × s, 18H each, CH_3); ^{13}C NMR (MeCN-d_3) δ 164.8 (s, CONH), 158.2, 157.8, 157.7 (3 × s, Pyr 2,2′and Bpy 2,2′), 153.8, 152.5 (2 × d, Pyr and Bpy 6,6′), 150.4, 150.4, 150.0 (2 × s, ArC−O), 149.2, 143.9 (2 × s, Ar ortho and Pyr 4,4′), 139.1 (d, Bpy 4,4′), 134.6, 134.5, 129.1, 128.8 (4 × s, Ar para), 128.6, 128.5 (2 × d, Bpy 3,3′), 126.8, 126.3 (2 × d, Bpy 5,5′), 126.8 (Ar meta), 122.1 (d, Pyr 5,5′), 75.1 (t, OCH_2), 40.4 (t, NCH_2), 34.9, 34.5 (2 × s, $C$$(CH_3)_3$), 31.7, 31.3 (2 × q, CH_3), 31.3, 31.1 (2 × t, $ArCH_2Ar$). Anal. Calcd for $C_{80}H_{90}F_{12}N_8O_8P_2Ru$: C, 57.11; H, 5.39; N, 6.663. Found: C, 57.08; H, 5.38; N, 6.54.

(h) Ruthenium(II) calix[4]arene receptor 12 was prepared from **10** (150 mg, 0.15 mmol) and $[RuCl_2(bipy)_2]\cdot 2H_2O$ (88 mg, 0.17 mmol) according to the procedure described above: yield 220 mg (85%); ^{1}H NMR (MeCN-d_3) δ 9.04 (br s, 2H, Pyr 3,3′), 8.52 (d, 4H, Bpy 3,3′), 8.22 (s, 2H, OH), 8.10 (m, 4H, Bpy 4,4′), 7.87 (d, 2H, Pyr 6,6′), 7.83 (m, 6H, Pyr and Bpy 6,6′), 7.68 (br s, 2H, CONH), 7.43 (m, 4H, Bpy 5,5′), 7.27, 7.21 (2 × s, 4H each, Ar meta), 4.36−4.28 (m, 8H, $ArCH_2$-Ar and OCH_2), 3.6 (br s, 4H, NCH_2), 3.45 (d, J = 13.2 Hz, 4H, $ArCH_2$-Ar), 2.49 (m, 4H, $CH_2CH_2CH_2$), 1.22, 0.74 (s, 18H each); ^{13}C NMR (MeCN-d_3) δ 164.3 (s, CONH), 158.1, 157.8 (2 × s, Pyr and Bpy 2,2′), 153.6, (2 × d, Pyr and Bpy 6,6′), 150.6, 150.1 (2 × s, ArC−O), 149.2, 143.7 (2 × s, Ar ortho), 143.5 (s, Pyr 4,4′), 139.1 (d, Bpy 4,4′), 135.1, 129.1 (2 × s, Ar para), 128.6, 126.6 (d, Bpy and Pyr 3,3′), 126.6, 126.2 (2 × d, Ar meta), 125.3, 122.9 (d, Bpy and Pyr 5,5′), 75.2 (t, OCH_2), 37.9 (t, NCH_2), 34.9, 34.5 (2 × s, $C$$(CH_3)_3$), 31.7 (t, $ArCH_2Ar$), 31.7, 31.4 (2 × q, CH_3), 29.6 (t, $CH_2CH_2CH_2$); MS-FAB *m/z* 1530 $[M - PF_6^- - 2H_2O]^+$. Anal. Calcd for $C_{82}H_{94}F_{12}N_8O_8P_2Ru$: C, 57.57; H, 5.54; N, 6.55. Found: C, 57.64; H, 5.59; N, 6.65.

Crystal Structure Determinations. Crystal data for the chloride complex of **1** and the dihydrogen phosphate complex of **11** are given in Table 2, together with refinement details. Data for both crystals were collected with Mo Kα radiation using the MARresearch image plate system. The crystals were loaded in thin glassed capillaries together with solvent and then positioned in an arbitrary orientation (chloride complex at 75 mm and phosphate complex at 90 mm from the X-ray source); 95 frames were measured at 2° intervals with a counting time of 5 min. Data analysis was carried out with the XDS program.[33] The structures were solved using direct methods with the SHELX-86 program.[34] For the chloride complex, all atoms in the $[Ru(bipy\ amide)(bipy)_2]^{2+}$ cation were clearly determined and non-hydrogen atoms were refined anisotropically and hydrogen atoms isotropically in calculated positions. Associated with the cation was one chloride anion. In addition, there were a large number of peaks in a different Fourier map indicative of solvent and an additional chloride anion. Five methyl cyanide molecules were also located, three with full occupancy and two with 0.75 occupancy. In addition nine peaks, all of 2−3 e/Å^3, were found which presumably represent a disordered anion and/or other solvent molecules though no obvious molecule was locatable. These atoms were refined as chlorine atoms with reduced occupancy. All these solvent/anion atoms were given isotropic thermal parameters, and hydrogen atoms were not included. The final occupancy of the peaks contributing to the disordered chloride anion amounted to 1.2, indicating that one or more peaks represented solvent rather than anion, although it was impossible to separate the various possibilities.

The structure of the dihydrogen phosphate complex was similarly difficult to determine in detail. There were two cations $[Ru(\mathbf{8})(bipy)_2]^{2+}$ in the asymmetric unit, each associated with one phosphate anion. In addition, there was one phosphate anion, several solvent molecules which were refined as three methyl cyanides with full occupancy, and two dimethyl sulfoxides, three ethanols, and nine water molecules all with 50% occupancy. The two cations were refined with all non-hydrogen atoms given anisotropic thermal parameters. Hydrogen atoms bonded to nitrogen and carbon were included in calculated positions, but those on oxygen could not be located and were not included. The

(33) Kabsch, W. *J. Appl. Crystallogr.* **1989**, *21*, 916.
(34) Sheldrick, G. M. SHELX-86 Program for Structure Solution. *Acta. Crystallogr.* **1990**, *A46*, 457.

three phosphates were also refined using anisotropic thermal parameters for the non-hydrogen atoms.

Clearly there is a problem with balancing the charge between cations and anions, and this is addressed under Results and Discussion. The solvent molecules were refined using isotropic thermal parameters for all atoms. The final refinements were carried out on F^2 using the SHELXL program.[35]

All calculations were carried out on a Silicon Graphics R4000 workstation at the University of Reading.

Acknowledgment. We thank the EPSRC for postdoctoral fellowships (F.S., D.H.), and a studentship (A.R.G.), the AFRC for a studentship (A.G.), Kodak Limited for studentships (S.W.D., A.J.G.), and the Trustees of the Analytical Chemistry Trust Fund of the Royal Society of Chemistry for the award of an SAC Research Studentship (J.S.W.). We also thank the EPSRC for use of the mass spectrometry service at University College Swansea and, with the University of Reading, for funds for the image plate system. Johnson Matthey is acknowledged for the generous loan of ruthenium trichloride.

(35) Sheldrick, G. M. SHELXL Program for Structure Refinement. University of Gottingen, 1993.
(36) Huang, J.; Brewer, G. *Can. J. Chem.* **1981**, *59*, 1689.

Supporting Information Available: Tables of positional parameters, bond lengths, bond angles, anisotropic thermal parameters, and hydrogen positions for (**1**)Cl and (**11**)H_2PO_4 (24 pages). Ordering information is given on any current masthead page.

IC960318L