Synthesis, Structure and Anion Co-ordination Chemistry of a Novel Macrocyclic Cobaltocenium Receptor†

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A new macrocyclic amide-substituted cobaltocenium receptor, 1,1′-[(ethylenedioxy)bis(ethyleneaminocarbonyl)]cobaltocenium hexafluorophosphate **2** has been prepared and its single-crystal X-ray structure determined. Proton NMR anion co-ordination studies revealed that **2** and other new acyclic cobaltocenium derivatives complex chloride and bromide anions with 1 : 1 stoichiometry. Comparative stability constant evaluations imply that the macrocyclic receptor **2** forms halide complexes of greatest thermodynamic stability, suggestive of a 'macrocyclic anion effect'. Cyclic voltammetric investigations showed the cobaltocenium receptors to electrochemically recognise halide anions.

There is considerable current interest in the synthesis of new receptors designed to selectively recognise anionic guest species of biomedical, medical and environmental importance.[1-3] As part of a research programme aimed at producing anion sensory reagents we have recently reported the first redox-responsive class of anion receptor based on the redox-active, pH-independent, positively charged cobaltocenium moiety.[4] A variety of mono- and acyclic 1,1′-bis-amide-substituted cobaltocenium receptors have been prepared and shown to complex and electrochemically sense halides, nitrate, hydrogen sulfate, dihydrogenphosphate and the dicarboxylate dianion adipate through a combination of mutual favourable electrostatic and amide CO ··· NH hydrogen-bonding interactions.[4,5]

In an attempt to impart a greater degree of receptor–anion guest thermodynamic stability and selectivity we report here the synthesis, structure and anion co-ordination chemistry of a new macrocyclic amide-substituted cobaltocenium derivative and provide evidence for a 'macrocyclic anion effect' with these types of receptor systems.

Experimental

Instrumentation.—Nuclear magnetic resonance 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 E.G. and G. Princeton Applied Research 362 scanning potentiostat. Elemental analyses were performed at the Inorganic Chemistry Laboratory, University of Oxford.

Solvent and Reagent Pretreatment.—Where necessary, solvents were purified prior to use and stored under nitrogen. Acetonitrile was predried over class 4 Å molecular sieves (4–8 mesh) and then distilled from calcium hydride. Unless stated to the contrary commercial grade chemicals were used without further purification.

1,1′-Bis(chlorocarbonyl)cobaltocenium chloride was prepared according to a literature procedure.[6]

Syntheses.—1,1′-*Bis*[(4-*hydroxyphenyl*)*aminocarbonyl*]-*cobaltocenium hexafluorophosphate* **1**. A solution of 4-aminophenol (0.69 g, 6.4 mmol) and triethylamine (0.65 g, 6.43 mmol) was made up in dry acetonitrile (150 cm^3) and stirred under nitrogen at room temperature. To this was added a solution of 1,1′-bis(chlorocarbonyl)cobaltocenium chloride (1.46 g, 3.2 mmol) in acetonitrile (120 cm^3) dropwise and under nitrogen. On addition, the solution changed from colourless to green and a bright red precipitate formed. The mixture was allowed to stir for 12 h, and the red solid was isolated by filtration as the crude product (1.81 g, 3 mmol, yield: 94%).

The crude product was taken up in hot water and excess NH_4PF_6 was added. On cooling, the pure product formed as fine red crystals which were isolated by filtration and dried in quantitative yield.

Crystals suitable for X-ray crystallographic determination were grown by dissolving the product in a minimum amount of acetonitrile–methanol, adding a few drops of water and allowing the most volatile solvent to evaporate leaving red rhombic-shaped crystals. NMR [$(CD_3)_2SO$]: ^{1}H, δ 6.03 (t, J = 1.95, 4 H, cp H), 6.41 (t, J = 2.01, 4 H, cp H), 6.72 (d, J = 8.8, 4 H, aryl H), 7.43 (d, J = 8.85 Hz, 4 H, aryl H), 9.42 (s, 2 H, OH) and 10.23 (s, 2 H, NH); ^{13}C, δ 85.12 (cp CH), 86.56 (cp CH), 95.82 (cp *C*–C=O), 114.98, 122.8, 129.5 (aryl CH and aryl CN), 154.5 (aryl COH) and 158.6 (C=O). FTIR: 3404 (NH), 1669 (C=O) and 836 cm^{-1} (PF_6^-). FAB MS: m/z 459 $(M - PF_6)^+$.

1,1′-[(*Ethylenedioxy*)*bis*(*ethyleneaminocarbonyl*)]*cobaltocenium hexafluorophosphate* **2**. A solution of 1,1′-bis(chlorocarbonyl)cobaltocenium chloride (1.1 g, 2.4 mmol) was made up in dry acetonitrile (100 cm^3) and stirred under nitrogen at room temperature. To this was added a solution of 2,2′-(ethylenedioxy)bis(ethylamine) (0.37 g, 2.5 mmol) and triethylamine (0.65 g, 6.4 mmol) in acetonitrile (100 cm^3) dropwise and under nitrogen over a period of 3 h. On addition, the solution changed from colourless to green-yellow. The mixture was allowed to stir for 24 h, Sephadex LH20 ($\approx$ 8 g) was added and the solvent was removed to give the crude product deposited on Sephadex as a bright green solid.

The crude product was purified by column chromatography using Sephadex LH20 and acetonitrile–methanol (1 : 1) as eluting solvent. Three main bands were collected; brown, golden yellow and bright yellow. The yellow fractions from the column were evaporated to dryness, redissolved in acetonitrile–methanol (1 : 1) and a few drops of a dilute solution of NH_4PF_6 were added. On standing, large cubic yellow crystals of the pure

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† *Supplementary data available:* see Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1995, Issue 1, pp. xxv–xxx.

Table 1 Crystal data and structure refinement for compounds **1** and **2**[a]

	1	**2**
Empirical formula	$C_{24}H_{24}CoF_6N_2O_6P$	$C_{18}H_{26}CoF_6N_2O_4P$
M	652.0	538.1
Crystal system	Triclinic	Monoclinic
Space group	$P\bar{1}$	$P2_1/c$
a/Å	20.290(12)	12.997(12)
b/Å	15.570(12)	13.266(11)
c/Å	8.170(8)	13.957(14)
α/°	93.70(1)	90
β/°	97.90(1)	104.5(1)
γ/°	88.10(1)	90
U/Å^3	2550.4	2329.8
D_c/g cm^{-3}	1.67	1.53
μ/mm^{-1}	0.820	0.785
F(000)	1304	1104
Crystal size/mm	0.2 × 0.2 × 0.2	0.3 × 0.3 × 0.3
θ range for data collection/°	1.01–24.72	< 25
Index ranges hkl	0–23, −18 to 18, −9 to 9	−13 to 13, 0–15, 0–16
Independent reflections	8607	2838
Refinement method	On F^2	On F
Data, parameters	8607, 761	1719, 307
Goodness-of-fit	1.064	1.125
Final R indices [$I > 2\sigma(I)$]	0.061 (R_1)[b] 0.197 (wR_2)[c]	0.063 (R)[b] 0.084 (R')[d]
R indices (all data)	0.083 (R_1) 0.274 (wR_2)	
Largest difference peak, hole/e Å^{-3}	0.79, −0.79	0.46, −0.39

[a] Details in common: $T = 293$ K, λ(Mo-Kα) = 0.7107 Å, $Z = 4$. [b] $R_1 = R = \Sigma||F_o| - |F_c||/\Sigma|F_o|$. [c] $wR_2 = [\Sigma w(F_o^2 - F_c^2)^2/\Sigma wF_o^2]^{\frac{1}{2}}$ where $w = [\sigma^2(F_o)^2 + (0.204P)^2 + 6.388P]^{-1}$, $P = [\max.(F_o^2, 0) + 2F_c^2]/3$. [d] $R' = [\Sigma w(|F_o| - |F_c|)^2/\Sigma wF_o^2]^{\frac{1}{2}}$ where $w^{-1} = \sigma^2(F) + 0.003F^2$.

monomeric PF_6^- product formed which were isolated, and of a standard suitable for X-ray crystallographic determination (0.42 g, 7.8 × 10^{-4} mol, yield: 33%). The brown fraction from the column appeared to contain the dimeric product. However all attempts to purify this product failed. NMR (CD_3CN): ^{1}H, δ 3.53 (q, J = 4, 4 H, NCH_2CH$_2$O), 3.70 (t, J = 4, 8 H, CH$_2$O), 5.85 (t, J = 2, 4 H, cp H), 5.96 (t, J = 2 Hz, 4 H, cp H) and 7.42 (s, 2 H, NH); ^{13}C, δ 40.6, 69.6, 70.7 (CH$_2$), 86.5, 87.4 (cp CH), 95.9 (cp *C*–C=O) and 161.9 (C=O). FTIR: 3448 (NH), 1662 (C=O) and 835 cm^{-1} (PF_6^-) (Found: C, 40.00; H, 3.90; N, 5.00. Calc. for $C_{18}H_{22}CoF_6N_2O_4P$: C, 40.45; H, 4.15; N, 5.25%). FAB MS: m/z 389 (M − PF_6)$^+$.

1,1′-Bis[(2-methoxyethyl)aminocarbonyl]cobaltoceniumhexafluorophosphate **3**. A solution of 2-methoxyethylamine (0.23 g, 3.1 mmol) and triethylamine (0.31 g, 3.1 mmol) was made up in dry acetonitrile (80 cm^3) and stirred under nitrogen at room temperature. To this was added a solution of 1,1′-bis(chlorocarbonyl)cobaltocenium chloride (0.71 g, 1.55 mmol) in acetonitrile (120 cm^3) dropwise and under nitrogen. On addition, the solution changed from colourless to green. The mixture was allowed to stir for 24 h, and the solvent was removed to give the crude product as a green semi-solid.

The crude product was purified by column chromatography using Sephadex LH20 and acetonitrile–methanol (3:1) as eluting solvent. Three main bands were collected; brown, green and yellow. The yellow fraction from the column was evaporated to dryness, taken up in hot water, and a saturated solution of NH_4PF_6 was added to precipitate the pure product as a bright yellow powder (0.66 g, 1.0 mmol, yield: 65%). NMR (CD_3CN): ^{1}H, δ 3.53 (s, 6 H, OCH$_3$), 3.53 (m, 4 H, CH$_2$), 3.60 (m, 4 H, CH$_2$), 5.79 (t, J = 2.2, 4 H, cp H), 6.47 (t, J = 2.2 Hz, 4 H, cp H) and 9.05 (s, 2 H, NH); ^{13}C, δ 40.0 (CH$_3$), 58.5, 70.4 (CH$_2$), 85.6 (cp CH), 87.8 (cp CH), 94.6 (cp *C*–C=O) and 163.5 (C=O). FTIR: 3245 (NH), 1658 (C=O) and 884 cm^{-1} (PF_6^-) (Found: C, 39.00; H, 5.00; N, 5.80. Calc. for $C_{18}H_{24}CoF_6N_2O_4P$: C, 40.30; H, 4.50; N, 5.20%).

Crystal Structure Determination of Compounds **1** *and* **2**.—Crystal data are given in Table 1, together with refinement details. Data for **1** were collected with Mo-Kα radiation using the MAR research image plate system. The crystal was positioned at 75 mm from the image plate. 95 Frames were measured at 2° intervals with a counting time of 2 min. Data analysis was carried out with the XDS program.[7] The data for **2** were collected on a STOE-2 diffractometer with the crystal rotating around the a axis. Data were measured *via* $\bar{\omega}$ scans. Background counts were for 20 s and a scan rate of 0.0333° s^{-1} was applied to a width of (1.5 + sin μ/tan θ). No decay in intensity was observed for the standard reflections. Both structures were solved using direct methods with the SHELX 86 program.[8] No absorption corrections were applied. In **1** two water molecules were located with 100% occupancy and four water molecules with 50% occupancy. In both structures, the non-hydrogen atoms were refined with anisotropic thermal parameters. The hydrogen atoms bonded to carbon and nitrogen atoms were included in geometric positions. Those bonded to oxygen atoms could not be located. The structure of **1** was refined using SHELXL[9] on a Silicon Graphics R4000 Workstation and of **3** using SHELX 76[10] on an Amdahl 5870, both at the University of Reading. Positional coordinates for **1** and **2** are listed in Tables 2 and 3, torsion angles for **2** in Table 4 and hydrogen bond details for **1** and **2** in Table 5.

Additional material available from the Cambridge Crystallographic Data Centre comprises H-atom coordinates, thermal parameters and remaining bond lengths and angles.

Results and Discussion

Syntheses and X-Ray Crystallography Studies.—Two synthetic routes were employed in attempts to prepare macrocyclic 1,1′-bis(amide)-substituted cobaltocenium derivatives. The first pathway involved the initial synthesis of a new cobaltocenium phenolic compound. The condensation of 1,1′-bis(chlorocarbonyl)cobaltocenium chloride[6] with 2 equivalents of 4-aminophenol in the presence of triethylamine gave a crude product which on dissolution in water and addition of excess ammonium hexafluorophosphate precipitated **1** as a red solid in excellent yield (Scheme 1).

Table 2 Atomic coordinates (× 10^4) for compound **1** with estimated standard deviations (e.s.d.s) in parentheses

Atom	*x*	*y*	*z*	Atom	*x*	*y*	*z*
P(1)	−1397(1)	172(1)	−3238(2)	C(42)	3825(2)	4826(3)	−3745(6)
F(1)	−683(4)	182(8)	−4179(14)	C(43)	3279(3)	5146(4)	−2745(7)
F(2)	−1369(4)	1195(3)	−3202(8)	C(44)	2657(3)	4769(3)	−2692(7)
F(3)	−2124(3)	229(5)	−2312(11)	O(45)	4441(2)	5206(3)	−3797(5)
F(4)	−1657(4)	230(4)	−4972(7)	Co(2)	5598(1)	1915(1)	−2575(1)
F(5)	−1116(4)	111(4)	−1550(8)	C(51)	6177(3)	1594(3)	−736(6)
F(6)	−1453(4)	−832(3)	−3198(8)	C(52)	6272(3)	972(3)	−1985(7)
P(11)	3502(1)	185(1)	−3194(2)	C(53)	5639(3)	620(4)	−2070(8)
F(11)	4255(3)	198(5)	−4047(9)	C(54)	5155(3)	1006(4)	−900(8)
F(12)	3498(3)	1208(3)	−3230(7)	C(55)	5489(3)	1609(4)	−76(7)
F(13)	2755(2)	202(3)	−2345(8)	C(56)	6673(3)	2135(4)	−114(7)
F(14)	3290(3)	220(4)	−4993(7)	O(57)	6503(2)	2814(3)	519(7)
F(15)	3736(4)	170(5)	−1453(7)	N(58)	7303(2)	1798(3)	−292(6)
F(16)	3503(3)	−833(3)	−3130(8)	C(60)	7981(3)	2981(4)	405(8)
Co(1)	555(1)	2080(1)	−2203(1)	C(61)	7830(2)	2113(3)	463(7)
C(11)	1194(3)	1630(3)	−589(7)	C(62)	8230(3)	1507(4)	1257(7)
C(12)	1237(3)	1084(4)	−1959(8)	C(63)	8757(3)	1769(4)	1964(8)
C(13)	583(3)	769(4)	−1995(8)	C(64)	8907(3)	2648(4)	1913(7)
C(14)	145(3)	1098(4)	−662(8)	C(65)	8519(3)	3253(4)	1124(8)
C(15)	519(3)	1630(4)	200(7)	O(66)	9438(3)	2861(4)	2657(7)
C(16)	1735(3)	2102(3)	19(7)	C(71)	4834(3)	2409(4)	−3787(9)
O(17)	1603(2)	2725(3)	861(7)	C(72)	5366(3)	2051(4)	−4926(8)
N(18)	2347(2)	1775(3)	−366(6)	C(73)	5963(3)	2492(4)	−4834(7)
C(20)	3167(3)	2874(4)	−180(7)	C(74)	5817(3)	3115(3)	−3619(7)
C(21)	2917(2)	2071(3)	306(6)	C(75)	5123(3)	3067(4)	−2968(8)
C(22)	3220(3)	1539(4)	1423(8)	C(76)	6250(3)	3757(3)	−3031(7)
C(23)	3762(3)	1823(4)	2076(8)	O(77)	5972(2)	4329(3)	−2171(6)
C(24)	4006(2)	2648(4)	1613(7)	N(78)	6905(2)	3675(3)	−3486(6)
C(25)	3714(3)	3166(4)	493(7)	C(81)	8053(3)	4093(4)	−3942(7)
O(26)	4542(2)	2882(3)	2325(6)	C(82)	8571(3)	4609(4)	−3663(8)
C(31)	818(3)	3282(4)	−3191(8)	C(83)	8446(3)	5271(4)	−2591(7)
C(32)	781(4)	2711(5)	−4469(9)	C(84)	7798(3)	5404(4)	−1805(7)
C(33)	121(4)	2391(6)	−4261(11)	C(85)	7294(3)	4879(4)	−2075(7)
C(34)	−248(4)	2740(5)	−2919(13)	C(86)	7412(3)	4229(3)	−3138(6)
C(35)	168(3)	3294(4)	−2213(11)	O(87)	8957(2)	5799(3)	−2393(7)
C(36)	1374(3)	3819(3)	−2839(7)	O(1)	2315(4)	1945(5)	−5110(9)
O(37)	1260(2)	4403(3)	−1889(7)	O(2)	7540(3)	2124(4)	−4940(7)
N(38)	1980(2)	3631(3)	−3646(6)	O(3)*	5369(5)	4025(6)	−8914(11)
C(39)	2593(2)	4075(3)	−3629(6)	O(4)*	5125(4)	4453(6)	−9227(11)
C(40)	3148(3)	3765(3)	−4640(6)	O(5)*	9807(5)	4465(6)	−8673(13)
C(41)	3757(3)	4140(3)	−4703(6)	O(6)*	9718(6)	4447(8)	−7322(15)

* Occupancy = 0.5.

Table 3 Atomic coordinates for compound **2** with e.s.d.s in parentheses

Atom	*x*	*y*	*z*	Atom	*x*	*y*	*z*
Co	2370(1)	197(1)	3997(1)	C(32)	3491(9)	5382(8)	3810(9)
C(11)	1180(6)	1049(9)	3130(9)	C(33)	2415(8)	5467(9)	3988(9)
C(12)	1136(7)	53(9)	2763(10)	O(34)	2281(5)	4617(6)	4596(6)
C(13)	1009(7)	−625(9)	3507(11)	C(35)	1260(9)	4560(9)	4763(11)
C(14)	972(8)	−37(8)	4306(10)	C(36)	1184(8)	3564(9)	5262(9)
C(15)	1078(6)	982(9)	4124(9)	N(37)	1213(6)	2744(7)	4578(7)
C(21)	3720(7)	867(8)	4839(9)	C(38)	1106(7)	1804(9)	4864(9)
C(22)	3530(7)	−70(10)	5243(10)	O(39)	1033(7)	1558(7)	5689(8)
C(23)	3547(7)	−833(8)	4521(10)	P(1)	−2131(2)	2477(2)	3515(3)
C(24)	3688(7)	−331(8)	3682(9)	F(1)	−2517(8)	2601(6)	2361(7)
C(25)	3808(5)	719(8)	3884(8)	F(2)	−1745(10)	2385(7)	4662(8)
C(26)	3990(6)	1444(8)	3125(9)	F(3)	−3179(9)	1942(11)	3489(10)
O(27)	3973(6)	1143(6)	2294(7)	F(4)	−1131(8)	3103(11)	3560(11)
N(28)	4199(6)	2388(7)	3421(7)	F(5)	−2723(9)	3503(8)	3600(8)
C(29)	4412(8)	3151(9)	2726(9)	F(6)	−1567(10)	1472(8)	3433(9)
C(30)	4520(7)	4168(9)	3155(10)	O(40)	3978(6)	1730(7)	342(7)
O(31)	3483(5)	4456(6)	3281(6)	O(41)	1546(7)	3344(8)	2684(7)

Crystals suitable for X-ray crystallographic structural determination were grown from aqueous methanol–acetonitrile. The asymmetric unit of **1** consists of two sets each of [cobaltocenium moiety], PF_6^-, $2H_2O$, with similar *y* and *z* coordinates but with *x* coordinates differing by *ca.* 0.5 of a cell length. The spatial arrangement of the two sets is therefore closely equivalent and one set is shown in Figs. 1 and 2.

The most interesting feature of the molecules is illustrated by the Figures; namely that in each molecule, one $C_5H_4C(O)NH$-

Table 4 Dihedral angles (°) for compounds **1** and **2** with e.s.d.s in parentheses

Compound **1**		Compound **2**	
C(16)–C(11)–C(12)–C(13)	178.4	C(13)–C(14)–C(15)–C(38)	−177.8
C(12)–C(11)–C(16)–N(18)	−24.0	C(14)–C(15)–C(38)–N(37)	179.9
C(11)–C(16)–N(18)–C(21)	−171.2	C(23)–C(24)–C(25)–C(26)	179.0
C(16)–N(18)–C(21)–C(22)	110.6	C(24)–C(25)–C(26)–N(28)	−173.3
C(36)–C(31)–C(32)–C(33)	−177.6	C(25)–C(26)–N(28)–C(29)	178.7
C(32)–C(31)–C(36)–N(38)	−14.1	C(26)–N(28)–C(29)–C(30)	174.3
C(31)–C(36)–N(38)–C(39)	175.6	N(28)–C(29)–C(30)–O(31)	−67.2
C(36)–N(38)–C(39)–C(40)	−177.3	C(29)–C(30)–O(31)–C(32)	172.5
C(56)–C(51)–C(52)–C(53)	178.3	C(30)–O(31)–C(32)–C(33)	−172.0
C(52)–C(51)–C(56)–N(58)	−25.6	O(31)–C(32)–C(33)–O(34)	62.1
C(51)–C(56)–N(58)–C(61)	−168.3	C(32)–C(33)–O(34)–C(35)	−175.5
C(56)–N(58)–C(61)–C(62)	−133.7	C(33)–O(34)–C(35)–C(36)	171.3
C(76)–C(74)–C(75)–C(71)	178.7	O(34)–C(35)–C(36)–N(37)	−67.1
C(75)–C(74)–C(76)–N(78)	169.5	C(35)–C(36)–N(37)–C(38)	−176.9
C(74)–C(76)–N(78)–C(86)	177.0	C(36)–N(37)–C(38)–C(15)	176.6
C(76)–N(78)–C(86)–C(81)	−170.6		

Table 5 Hydrogen-bond contacts (Å)

Compound **1**

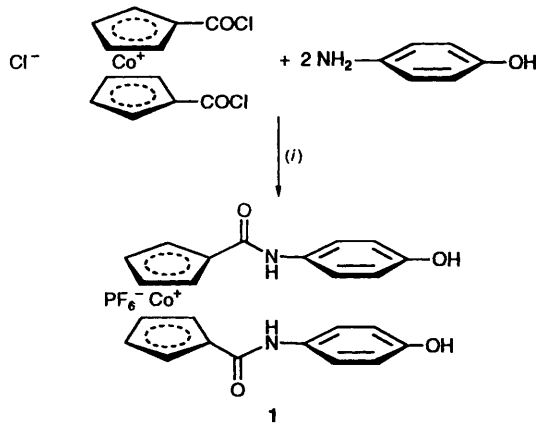
N(18) ··· F(13)	3.050	O(45) ··· O(45^{III})	2.874
O(17) ··· O(87^{I})	2.819	O(66) ··· O(6^{II})	2.553
O(26) ··· O(3^{II})	2.552	O(66) ··· O(5^{II})	2.744
O(26) ··· O(4^{II})	2.893	O(77) ··· O(4^{II})	2.771
O(37) ··· O(5^{III})	2.753	O(77) ··· O(4^{III})	3.025
O(37) ··· O(6^{III})	2.744	O(87) ··· O(5^{V})	2.776
N(38) ··· O(1)	2.975	O(87) ··· O(6^{V})	2.683
O(45) ··· O(3^{III})	2.663	O(1) ··· F(6^{VI})	3.028
O(45) ··· O(4^{III})	2.821	O(2) ··· F(2^{IV})	3.065

Symmetry equivalent positions: I $1 - x, 1 - y, -z$; II $x, y, 1 + z$; III $1 - x, 1 - y, -z - 1$; IV $1 + x, y, z$; V $2 - x, 1 - y, -z - 1$; VI $-x, -y, -z - 1$.

Compound **2**

O(41) ··· O(27)	2.84	O(42) ··· O(31)	2.86
O(41) ··· N(28^{I})	3.00	O(42) ··· O(34)	3.10
O(41) ··· O(31^{I})	3.20	O(42) ··· N(37)	2.90
O(41) ··· O(34^{I})	2.83	O(42) ··· O(39^{I})	2.70

Symmetry equivalent positions: I, $x, 0.5 - y, 0.5 + z$.



1

Scheme 1 (*i*) $2NEt_3$, MeCN, NH_4PF_6

C_6H_4OH moiety is approximately planar while in the other the phenyl ring is twisted well out of that plane (respective angles in first molecule 12.8, 89.1° and in second molecule 4.1, 68.0°).

There is an extensive pattern of hydrogen bonding in the unit cell and the closest distances are listed in Table 5. Numerous attempts were made at producing the desired macrocyclic derivatives *via* the reaction of **1** with 2 equivalents of base (NaH or NaOEt) and subsequent addition of bis(bromoalkanes). The major isolated product from all these reactions was always the starting material **1** and so an alternative synthetic strategy was undertaken.

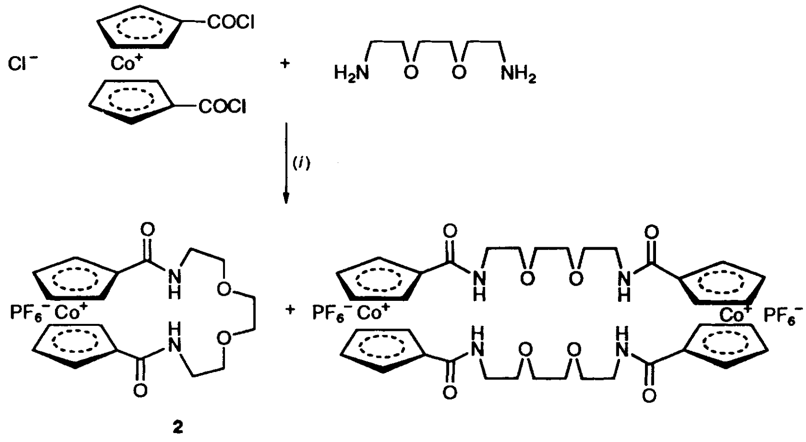
1,1′-Bis(chlorocarbonyl)cobaltocenium chloride was reacted under high dilution conditions in dry acetonitrile with 1 equivalent of 2,2′-(ethylenedioxy)bis(ethylamine) in the presence of triethylamine. Sephadex column chromatography using acetonitrile–methanol eluent produced a major yellow product which on addition of excess ammonium hexafluorophosphate gave the monomeric macrocycle **2** as yellow cubic crystals in 33% yield (Scheme 2). Later fractions from the Sephadex column appeared from fast atom bombardment mass spectrometric analysis to contain small amounts of the dimeric derivative which could not unfortunately be obtained in sufficient quantities for anion co-ordination studies (Scheme 2).

The yellow crystals of **2** were of sufficient quality for X-ray crystallographic structural analysis.

The structure of **2** (Figs. 3 and 4) consists of discrete cations and anions and two water molecules. The water molecules form an elaborate system of intermolecular hydrogen bonds with the macrocycle. Thus O(40) has close contacts with O(27) (2.84 Å) in one molecule and N(28) (3.00 Å), O(31) (3.20 Å) and O(34) (2.83 Å) in another, while O(41) has close contacts with O(39) in one molecule and O(31) (2.86 Å), O(34) (3.10 Å) and N(37) (2.90 Å) in another. The conformation of the macrocycle is illustrated by the torsion angles in Table 4 and shows that the macrocycle has approximate C_2 symmetry.

In order to seek any evidence in subsequent anion co-ordination investigations of a 'macrocyclic anion effect' with these types of cobaltocenium receptor systems the acyclic structurally similar analogue (**3**) to the macrocyclic derivative **2** was prepared in 65% yield using the synthetic route outlined in Scheme 3.

Anion Co-ordination Studies–Stability-constant Determinations from ^1H NMR *Titrations.*—The addition of tetrabutylammonium chloride and bromide salts to $(CD_3)_2SO$ solutions of **1**–**3** resulted in significant perturbations of the respective protons of all three receptors. As noted in previous anion studies with simple mono(arylamide)cobaltocenium derivatives[4] substantial downfield shifts of the amide (Fig. 5) and cyclopentadienyl protons are noteworthy. The resulting titration curves suggest a cobaltocenium receptor–halide anion stoichiometry of 1 : 1. The computer program EQNMR [11] was used to estimate the stability constants from the ^1H NMR titration data and the results are summarised in Table 6. A comparison of the relative magnitudes of stability constants suggest the macrocyclic cobaltocenium receptor **2** forms halide complexes of greatest thermodynamic stability. This is especially noteworthy when comparing the stability constant



Scheme 2 (*i*) $2NEt_3$, MeCN, NH_4PF_6

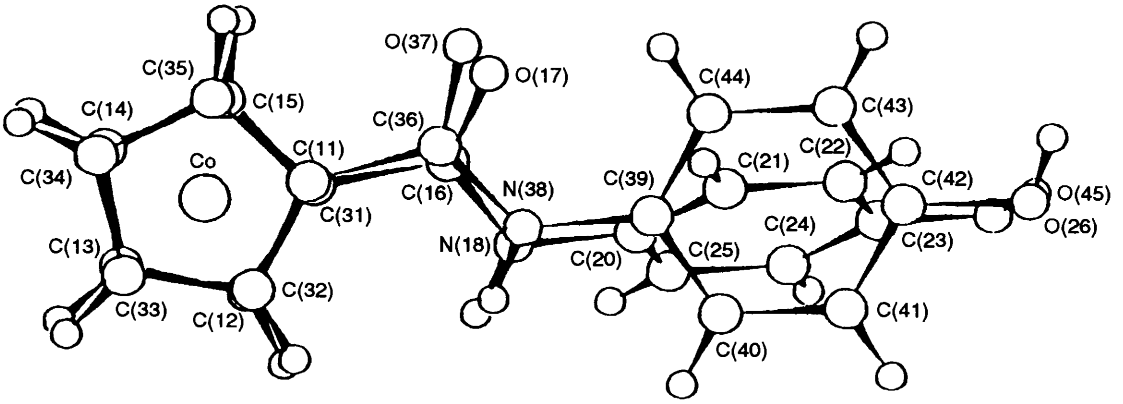


Fig. 1 Structure of compound **1**

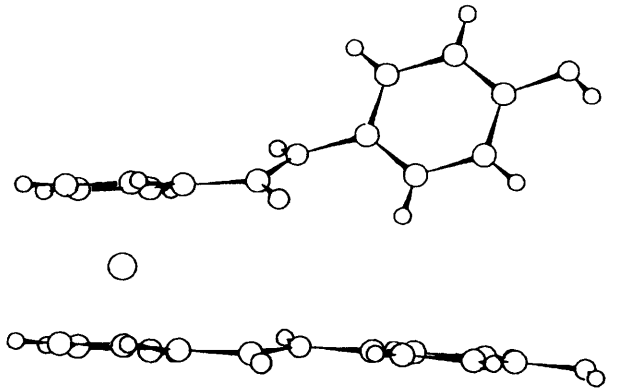


Fig. 2 Structure of compound **1** illustrating the relative positions of the phenyl rings

Table 6 Stability constant data for compounds **1**–**3** with chloride and bromide anions in $(CD_3)_2SO$

Receptor	Anion	K*/dm^3 mol^{-1}
1	Cl^-	32
1	Br^-	60
2	Cl^-	250
2	Br^-	100
3	Cl^-	20
3	Br^-	15

* Errors estimated to be ⩽ 10%.

Table 7 Electrochemical data

Compound	$E_{\frac{1}{2}}{}^a$/V	Anion	$\Delta E_{\frac{1}{2}}{}^b$/mV
1	−0.86	Cl^-	40
		Br^-	20
3	−0.90	Cl^-	35
		Br^-	20
5	−0.88	Cl^-	35

[a] Obtained in acetonitrile solution containing 0.2 mol dm^{-3} NBu_4BF_4 as supporting electrolyte. Solutions were *ca.* 1×10^{-3} mol dm^{-3} in receptor and potentials were obtained with reference to a Ag–Ag$^+$ electrode. [b] Cathodic shift in reduction potential produced by presence of anions (up to 5 equivalents) added as their tetrabutylammonium salts.

values of the macrocycle **2** and this receptor's acyclic analogue **3** with the anion Cl^-, where there is an order of magnitude difference. This observation clearly indicates the existence of a 'macrocyclic anion effect' with this class type of anion receptor.

Electrochemical Anion Recognition Studies.—The electrochemical properties of the three cobaltocenium derivatives were investigated in acetonitrile using cyclic voltammetry with NBu_4BF_4 as the supporting electrolyte. Each compound exhibited a reversible redox reduction wave in the region −0.8 to −0.9 V *vs.* Ag–Ag$^+$ electrode (Table 7). Cyclic voltammograms were also recorded after progressively adding stoichiometric equivalents of halide anion guests to the electrochemical solutions, and the results are also summarised in Table 7. Significant one-wave cathodic shifts of the cobaltocenium–cobaltocene redox couples of all three receptors are observed,

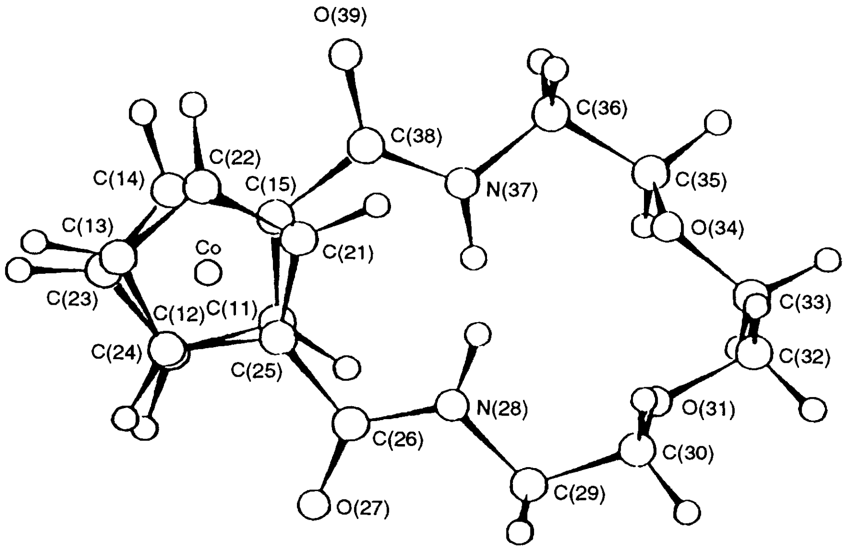


Fig. 3 Structure of compound **2** looking down the metallocene axis

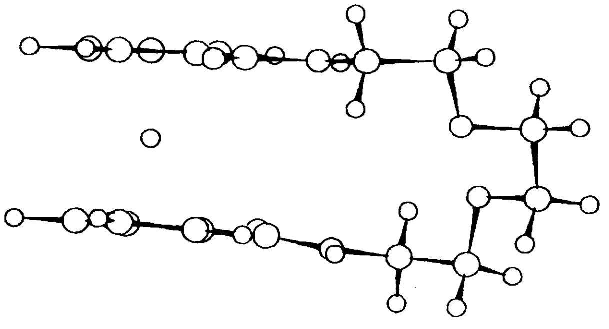
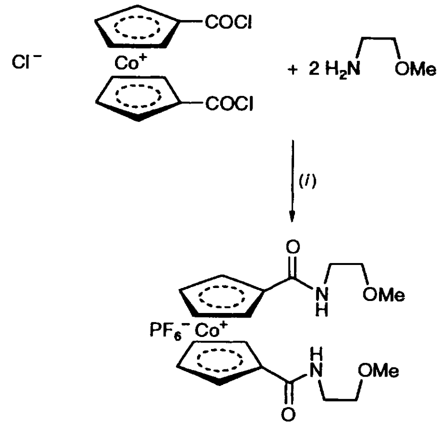


Fig. 4 Structure of compound **2**



3

Scheme 3 (*i*) $2NEt_3$, MeCN, NH_4PF_6

with chloride by virtue of its higher charge density producing relatively larger magnitudes of shift than the bromide anion.

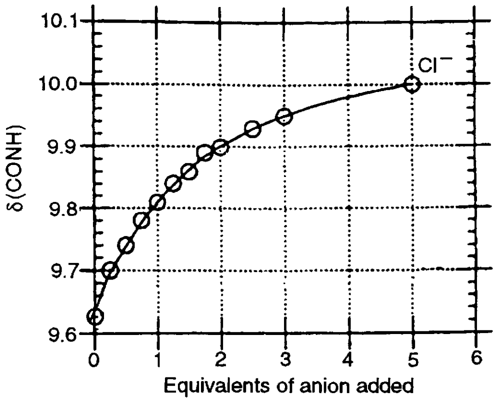


Fig. 5 Proton NMR titration of **1** and chloride anions in $(CD_3)_2SO$

Conclusion

A new macrocyclic amide-substituted cobaltocenium receptor **2** has been prepared and its single-crystal X-ray structure determined. Proton NMR halide anion co-ordination investigations in $(CD_3)_2SO$ revealed that **2** and acyclic analogues **1** and **3** complex Cl^- and Br^- in a 1:1 stoichiometric fashion. Stability-constant evaluations suggest the macrocyclic cobaltocenium receptor **2** forms halide complexes of greatest thermodynamic stability giving experimental evidence for the existence of a 'macrocyclic anion effect'. Electrochemical investigations reveal all three cobaltocenium derivatives can electrochemically recognise halide anions with chloride producing larger cathodic perturbations than bromide because of its relatively higher charge density.

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References

1 B. Dietrich, *Pure Appl. Chem.*, 1993, **65**, 1457; J.-L. Pierre and P. Baret, *Bull. Soc. Chim. Fr.*, 1983, 367; B. Dietrich, in *Inclusion Compounds*, eds. J. L. Atwood, J. E. D. Davies and D. D. MacNicol, Academic Press, New York, 1984, vol. 2, p. 337; F. P. Schmidtchen, *Nachr. Chem. Tech. Lab.*, 1988, **36**, 8.

2 M. W. Hosseini, A. J. Blackler and J.-M. Lehn, *J. Am. Chem. Soc.*, 1990, **112**, 3896 and refs. therein; F. P. Schmidtchen, *J. Org. Chem.*, 1986, **51**, 5161; P. D. Beer, J. W. Wheeler, A. Grieve, C. Moore and T. Wear, *J. Chem. Soc., Chem. Commun.*, 1992, 1225; H. Furuta, M. Cyr and J. L. Sessler, *J. Am. Chem. Soc.*, 1991, **113**, 6677.

3 H. E. Katz, *Organometallics*, 1987, **6**, 1134; J. D. Wuest and B. Zacharie, *J. Am. Chem. Soc.*, 1987, **109**, 4714; M. T. Blandon, J. N. Horner and M. Newcomb, *J. Org. Chem.*, 1989, **54**, 4626; M. T.

Reetz, C. M. Niemeyer and K. Harms, *Angew. Chem., Int. Ed. Engl.*, 1991, **30**, 1472; D. M. Rudkevich, W. P. R. V. Stauthamer, W. Verboom, J. F. J. Engbersen, S. Harkema and D. N. Reinhoudt, *J. Am. Chem. Soc.*, 1992, **114**, 9671.

4 P. D. Beer, C. Hazelwood, D. Hesek, J. Hodacova and S. E. Stokes, *J. Chem. Soc., Dalton Trans.*, 1993, 1327; P. D. Beer, M. G. B. Drew, A. R. Graydon, D. K. Smith and S. E. Stokes, *J. Chem. Soc., Dalton Trans.*, 1995, 403.

5 P. D. Beer, M. G. B. Drew, C. Hazelwood, D. Hesek, J. Hodacova and S. E. Stokes, *J. Chem. Soc., Chem. Commun.*, 1993, 229; P. D. Beer, D. Hesek, J. Kingston, D. K. Smith and M. G. B. Drew, *Organometallics*, 1995, **14**, 3288.

6 J. E. Sheats and M. D. Rausch, *J. Org. Chem.*, 1970, **35**, 3245.

7 W. Kabsch, *J. Appl. Crystallogr.*, 1988, **21**, 916.

8 G. M. Sheldrick, SHELX 86, *Acta Crystallogr., Sect. A*, 1990, **46**, 467.

9 G. M. Sheldrick, SHELXL, Program for crystal structure refinement, University of Göttingen, 1993.

10 G. M. Sheldrick, SHELX 76, Package for crystal structure analysis, University of Cambridge, 1976.

11 M. J. Hynes, *J. Chem. Soc., Dalton Trans.*, 1993, 311.

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