Multi Redox-active Macrocyclic Host Molecules containing Multiple Benzo Crown Ether and Ferrocenyl Moieties that bind Bipyridinium Dications: Syntheses, Co-ordination and Electrochemical Properties

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The design, syntheses, co-ordination and electrochemical properties of novel multisite host molecules containing multiple benzo crown ether and ferrocenyl redox centres are described. The reaction of the macrocycle 2,8,14,20-tetraferrocenylpentacyclo[19.3.1.1.^{3,7}1^{9,13}.1^{15,19}]octacosa-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-dodecaen-4,6,10,12,16,18,22,24-octol **3** with propionic anhydride, benzoyl chloride or chlorocarbonylferrocene **6** gave new redox-active host molecules **4**, **5** and **7** respectively. The acid-catalysed condensation of 15-formyl-2,3,5,6,8,9,11,12-octahydro-1,4,7,10,13-benzopentaoxacyclopentadecine with 1,3-dihydroxybenzene afforded a novel phenolic macrocycle 2,8,14,20-tetrakis(2,3,5,6,8,9,11,12-octahydro-1,4,7,10,13-benzopentaoxacyclopentadecin-15-yl)-pentacyclo[1.3.1.1^{3,7}.1^{9,13}.1^{15,19}]octacosa-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-dodecaen-4,6,10,12,16,18,22,24-octol **14** which on reaction with propionic anhydride, benzoyl chloride, **6** or bromochloromethane gave respective host molecules **15**, **16**, **17** and **18** (the latter being the first crown ether cavitand host), each containing four benzo-15-crown-5 moieties. Electrochemical studies show the four ferrocenyl redox centres present in **5** to undergo two one-electron oxidations at +0.58 and +0.67 V in dichloromethane. Redox-active host **17**, containing eight ferrocenyl moieties, was found to undergo independent reversible one-electron oxidations in dichloromethane. High-field ^{1}H NMR complexation studies revealed hosts **16–18** to form solution complexes with bipyridinium guest species, exclusively at the host's benzo crown ether binding site.

The condensation of 1,3-dihydroxybenzene with simple alkyl and aryl aldehydes under acidic conditions has been shown to give tetrameric cyclic octols.[1,2] These phenolic macrocycles can be thought of as a type of calix[4]arene ([1.1.1.1]metacyclophane-7,14,21,28-tetrol)[3] in which the eight hydroxyl groups are positioned *exo* with respect to the macrocyclic hydrophobic cavity instead of *endo* as in the calix[4]arenes. Hogberg made a careful study of the reactions of acetaldehyde[4] and benzaldehyde[5] with 1,3-dihydroxybenzene and found that only two configurational isomers were formed in reasonable yields. The kinetic product, the *cis-trans-cis* isomer, has a chair-type conformation, which can be converted *in situ* into the less-soluble thermodynamic product, the all-*cis* isomer, which has a boat-type conformation. Further recent studies of a number of condensations by Cram and co-workers[6] indicate that aliphatic aldehydes and 1,3-dihydroxybenzene give good yields of the all-*cis* isomer, while benzaldehyde or 4-substituted benzaldehydes produce the all-*cis*, the *cis-trans-cis*, or a mixture of the two isomers. A third *cis-trans-trans* isomer has also recently been reported from the condensation reaction with lipophilic aldehydes.[7]

The incorporation of Lewis-acid binding sites and multiple redox-active centres[8,9] into this type of macrocyclic system will lead to prototypes of a new class of redox catalytic system capable of promoting redox reactions on a guest substrate such as CO_2 or CO, through a combination of guest inclusion and subsequent Lewis-acid catalytic activation (Fig. 1). Towards this goal this paper describes the preparation, co-ordination and electrochemical properties of novel multisite host molecules containing multiple benzo crown ether and ferrocenyl moieties. A preliminary report of this work has been published.[10]

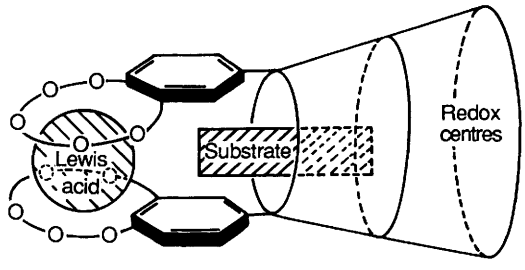

Fig. 1 General representation of a new class of redox catalytic system, capable of promoting redox reactions on a guest substrate *via* guest inclusion and Lewis-acid catalytic activation

Results and Discussion

Hogberg[5] has observed that prolonged heating in the acid-catalysed condensation of 1,3-dihydroxybenzene with benzaldehyde resulted in the exclusive formation of the *cis-cis-cis* isomer. The boat-type conformation of this isomer provides the basis for a hydrophobic cavity, unlike the other possible isomers. Consequently in each of the present condensations heating was employed for at least 4 h to ensure that only the *cis-cis-cis* isomer was formed in good yield.

The reaction of ferrocenecarbaldehyde **1** and 1,3-dihydroxybenzene **2** in the presence of hydrochloric acid and ethanol gave the insoluble phenolic macrocycle **3**[9] (Scheme 1). In an effort to solubilise this product a number of acylation reactions were

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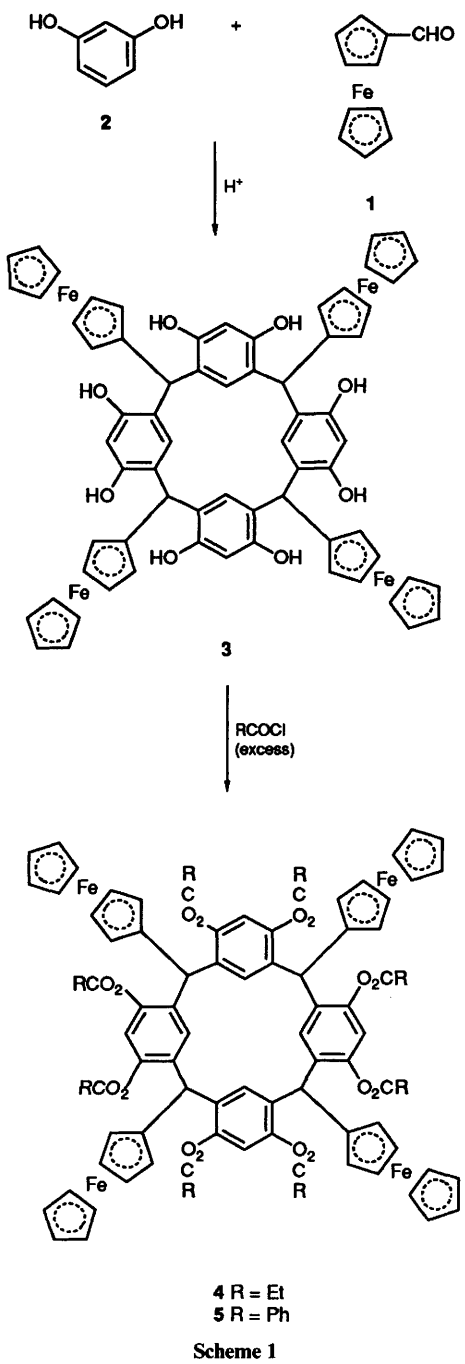
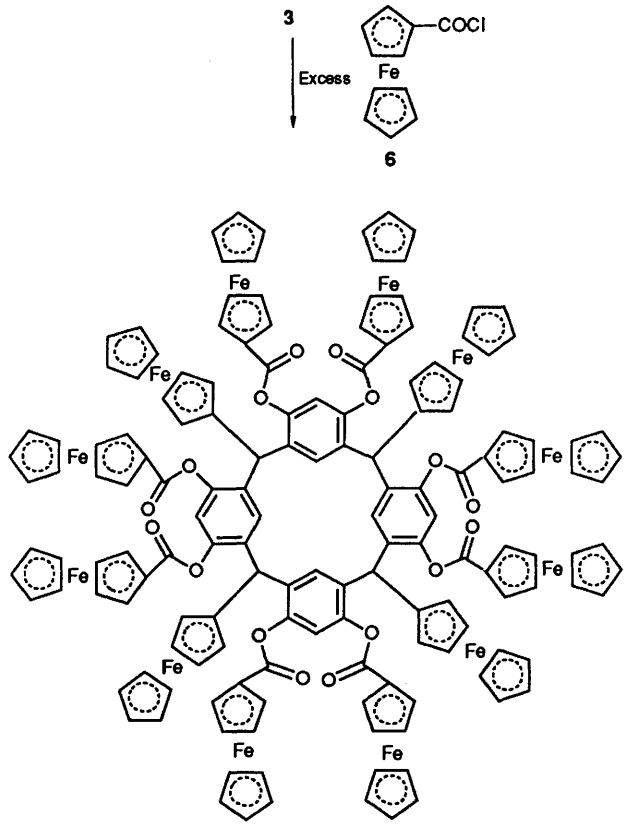
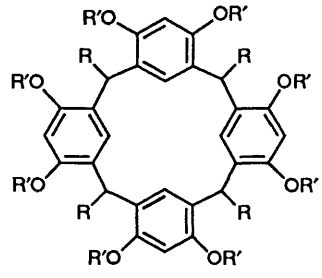


Scheme 1



Scheme 2

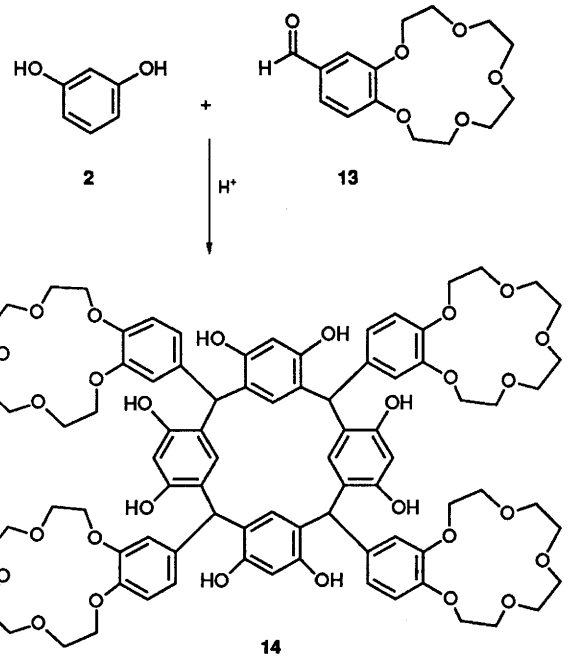


	R	R'		R	R'
8	Me	H	**19**	Me	COMe
9	Ph	H	**20**	Me	COEt
10	Me	COPh	**21**	Ph	COPr
11	Ph	COPh	**22**	C_6H_4Br	COPr
12	Me	$(COC_5H_4)Fe(C_5H_5)$			

carried out. The reaction of **3** with an excess of propionic anhydride in the presence of pyridine produced **4** as an orange-brown powder (83% overall yield for the two steps). Treatment of a tetrahydrofuran suspension of **3** with benzoyl chloride in the presence of triethylamine and 4-dimethylaminopyridine, followed by chromatographic separation gave **5** as an orange crystalline solid. The analogous procedure using chlorocarbonylferrocene **6**[11] gave octaester **7** as an orange-red powder (Scheme 2). Related compounds **10–12** were synthesised from the respective octol **8**,[4] **9**[9] and appropriate acid chloride.

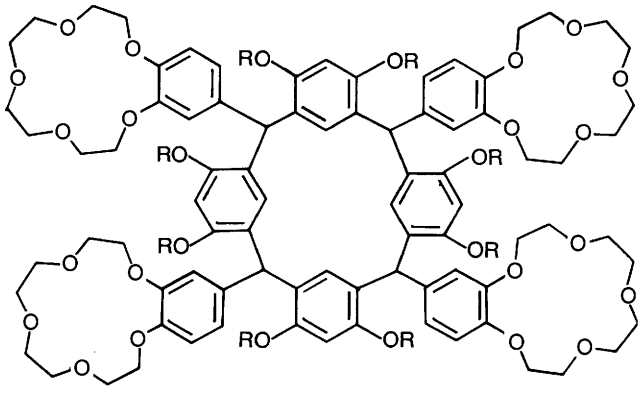
Having established a simple synthetic method for introducing redox-active centres into a macrocyclic structural framework the incorporation of Lewis-acid binding sites was investigated. The acid-catalysed condensation of 1,3-dihydroxybenzene **2** with 4′-formylbenzo-15-crown-5 (15-formyl-2,3,5,6,8,9,11,12-octahydro-1,4,7,10,13-benzopentaoxacyclopentadecine) **13**[12] gave the novel tetrameric phenolic benzo crown ether macrocycle **14** as a white powdery solid, Scheme 3. This compound was acylated using propionic anhydride, benzoyl chloride and chlorocarbonylferrocene in the presence of base to give octa-esters **15**, **16** and **17** in overall yields of 43, 21 and 22% respectively. Treatment of **14** with bromochloromethane in dry dimethylformamide and K_2CO_3 produced the first crown ether cavitand[13] host molecule **18** (Scheme 4). The structures of all the acylated products and the cavitand were confirmed by infrared, ^1H and ^{13}C NMR spectroscopy and fast atom bombardment (FAB) mass spectrometry (see Experimental section). The elemental analyses generally showed good agreement between the values expected and those obtained, however the small discrepancies found for some compounds was attributed to their ability to include solvent molecules, which proved difficult to remove even under vacuum.

The X-ray crystal structure of compound **5** has recently been determined[14] and reveals the expected *cis-cis-cis* isomer. Numerous dichloromethane solvent molecules were found to be

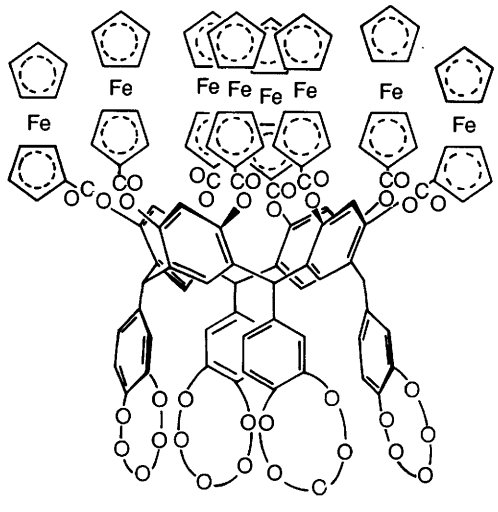


2 13 14

Scheme 3



15 R = COEt
16 R = COPh



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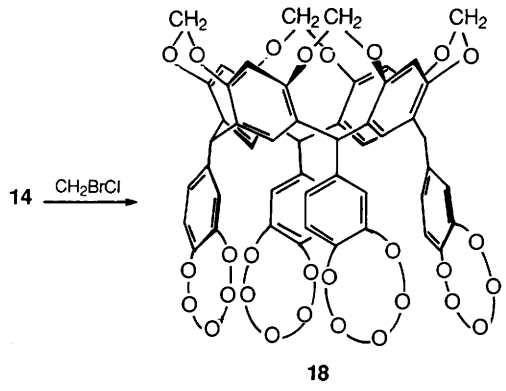

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Scheme 4

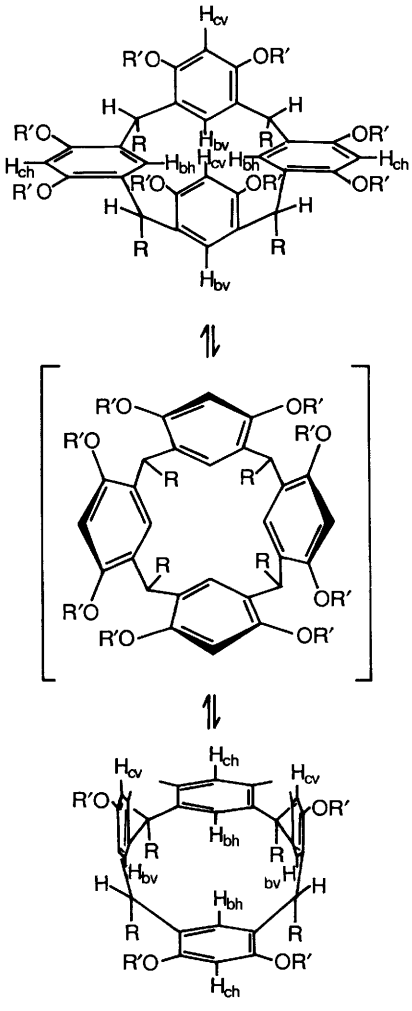


Fig. 2 Interconversion of horizontal and vertical 1,3-diacylaryl units

included in the crystal lattice and this has thwarted refining the structure to an acceptable level for publication.

Variable-temperature ^{1}H *NMR Studies.*—Högberg[4,5] demonstrated that the ^{1}H NMR spectra of the acylated *cis-cis-cis* isomers from the condensations of 1,3-dihydroxybenzene with acetaldehyde, benzaldehyde or 4-bromobenzaldehyde showed a characteristic temperature dependence. The pattern of the chemical shifts of the aromatic protons indicated whether the interconversion of the vertical and horizontal 1,3-diacylaryl units was fast on the NMR time-scale at ambient temperature (Fig. 2).

The protons H_b and H_c each gave rise to a pair of singlets whilst this interconversion was slow on the NMR time-scale,

Table 1 Proton NMR chemical shifts of selected aromatic protons in $CDCl_3$ at ambient temperature

Compound	R[a]	R'[a]	H_b[a]	H_c[a]
19	Me	COMe	Collapsed	6.88[4,b]
20	Me	COEt	5.95, 7.30[c]	6.86[4,b]
21	Ph	COPr	5.89, 6.15	6.91, 7.02[5,d]
22	C_6H_4Br	COPr	5.76, 6.07	6.93, 6.99[5,d]
4	$(C_5H_4)Fe(C_5H_5)$	COEt	Collapsed	6.21[e]
5	$(C_5H_4)Fe(C_5H_5)$	COPh	6.64, 8.00	6.72, 6.74[e]
7	$(C_5H_4)Fe(C_5H_5)$	$(COC_5H_4)Fe(C_5H_5)$	Collapsed	6.72[e]
12	Me	$(COC_5H_4)Fe(C_5H_5)$	6.34, 7.65	7.06, 7.14[e]
15	Benzo-15-crown-5	COEt	6.53, 6.55	6.87, 6.91[e]

[a] R, R', H_b and H_c are as shown in Fig. 2. [b] At 60 MHz. [c] These peaks were very broad, near collapse. [d] At 200 MHz. [e] At 270 MHz.

Table 2 Electrochemical data*

Compound	E_{pa}/V	E_{pc}/V
5	0.64, 0.73	0.56, 0.65
12	0.88	0.78
17	0.87	0.77
Ferrocene	0.60	0.52

* Obtained from dichloromethane solutions which were 1×10^{-3} mol dm^{-3} in each compound and 0.2 mol dm^{-3} in $[NBu_4][BF_4]$ (supporting electrolyte). Values are quoted relative to the saturated calomel electrode (SCE) and are uncorrected for internal resistance. Scan rate 200 mV s^{-1}.

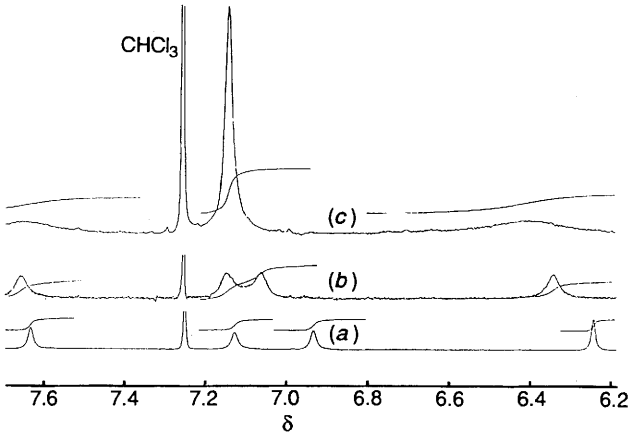


Fig. 3 The ^1H NMR spectra of the aromatic protons of compound **12** in $CDCl_3$ at (*a*) 223, (*b*) 294 and (*c*) 323 K

but the values of the chemical shifts depended on the nature of substituents R. When R was a phenyl derivative H_{bh} and H_{bv} were shielded by the nearby 1,3-diacylaryl rings or by the R substituents respectively, and so were both shifted relatively upfield. As the temperature was increased, and interconversion became fast on the NMR time-scale, each pair of singlets corresponding to H_b and H_c respectively coalesced to give a singlet. However, when R was not a phenyl derivative H_{bh} was still shielded by the 1,3-diacylaryl rings, but H_{bv} was no longer affected by aromatic ring currents and so gave rise to a chemical shift much further downfield. As the temperature was increased in these cases the two singlets corresponding to H_c coalesced, and the two more distant H_b singlets broadened and eventually collapsed.

The ^1H NMR chemical shifts of H_b and H_c of some of the novel acylated products are listed in Table 1, together with those of some of the *cis-cis-cis* isomers of compounds synthesised by other workers (**19–22**).[4,5] Compounds **10**, **11**, **16** and **17** exhibited a very complicated pattern in the aromatic region, even using high-field spectrometers, and so H_b and H_c could not be assigned with any certainty. The data in Table 1 indicate that the coalescence temperatures of H_b and H_c within compounds **4** and **7** were below or at ambient temperature, and those of **5**, **12** and **15** were above it. The ^1H NMR spectra of **12** in $CDCl_3$ at 223, 294 and 323 K are shown in Fig. 3, to demonstrate the pattern of chemical shifts of H_b and H_c below, near and above the coalescence temperature of this compound.

The relative complexity of the 22.5 MHz ^{13}C NMR spectra of all the acylated compounds indicated whether the coalescence temperature had been reached at ambient temperature. In particular, if a compound only exhibited one carbonyl carbon signal (**4**, **7**, and **10**), interconversion of the horizontal and vertical 1,3-diacylaryl units was fast on the NMR time-scale at ambient temperature, while those compounds which exhibited two carbonyl carbon signals (**5**, **11**, **12**, **15–17**) were still undergoing relatively slow interconversion.

It was possible to deduce some useful information about the electronic environments of the multiple ferrocene units within each redox-active compound from their ^1H NMR spectra. The four ferrocenyl moieties in **4** were seen to be electronically equivalent, while the pattern of ferrocenyl chemical shifts of **5** suggested that there were two slightly different electronic environments each occupied by two ferrocenyl groups. The ^1H NMR spectra of compounds **12** and **17**, each containing eight ferrocenecarboxyl groups, also indicated the presence of two slightly different electronic environments for those groups, probably a result of the slow interconversion of the horizontal and vertical 1,3-diferrocenecarboxyaryl units on the NMR time-scale. The ferrocenyl and ferrocenecarboxyl signals in the spectrum of compound **7** were too broad to allow close examination of the chemical shifts.

Electrochemical Studies.—The electrochemical properties of the acylated redox-active molecules **5**, **12** and **17** were studied by cyclic voltammetry.* The values obtained for the peak potentials of the anodic and cathodic waves (E_{pa} and E_{pc} respectively) for the oxidation processes are given in Table 2.

Compound **5**, which contains four ferrocenyl groups, gave a cyclic voltammogram consisting of two reversible oxidation waves, *ca.* 90 mV apart (Fig. 4). A study of this electrochemical process by differential pulse voltammetry showed two separate peaks at +0.58 and +0.67 V of approximately equal height, suggesting that each peak represented two one-electron processes, assuming that the combined peaks corresponded to four one-electron processes. Interestingly, the ^1H and ^{13}C NMR spectra and the X-ray crystal structure of **5**[14] indicated that there are two different ferrocenyl environments, each occupied by two groups within this molecule. Therefore, taking into account these observations, the cyclic voltammogram of **5** most likely represents two reversible two-electron transfers, the presence of two waves being the result of the two different ferrocenyl electronic environments. In contrast, with the redox-active cavitand host molecule **23**[9] all four ferrocene

* The electrochemical properties of compound **7** are complicated and are currently under investigation.

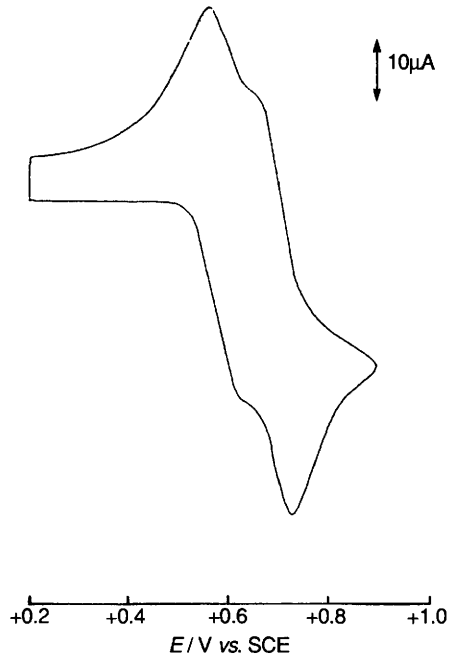
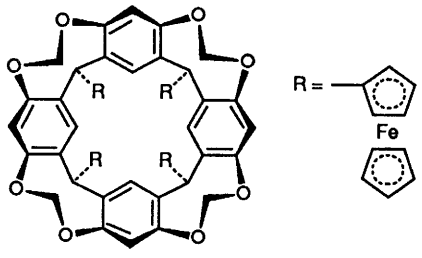


Fig. 4 Cyclic voltammogram of compound **5**



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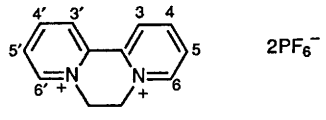

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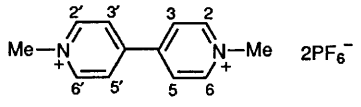

25

centres are oxidised in four one-electron processes at the same potential.

The cyclic voltammograms of compounds **12** and **17** were very similar suggesting that the nature of the four axial substituents (methyl and benzo-15-crown-5) had little effect on the electronic environment of the relatively distant ferrocenecarboxyl redox centres within each molecule. In both cases only one oxidation wave is observed indicating that all eight ferrocenecarboxyl units of **12** and **17** are essentially electronically equivalent and undergo independent reversible one-electron transfer at the same potential.

Controlled-potential electrolyses of compounds **5**, **12** and **17** were repeatedly attempted in order to confirm that all the redox-active ferrocene centres were undergoing electron transfer at the same or similar electrode potentials. However, these investigations were unsuccessful due to the gradual coating of material on the electrode surface as electrolysis progressed. This would suggest that the electrochemical reactions of these compounds are not completely reversible under the conditions of controlled-potential electrolysis.

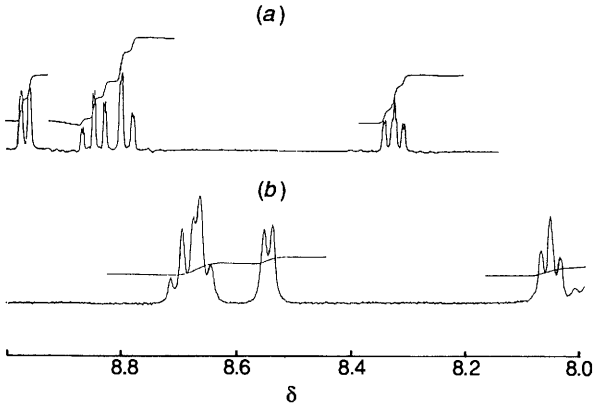

Fig. 5 The ^{1}H NMR spectra of the bipyridyl protons of compound **24** (*a*) alone and (*b*) after addition of 1 equivalent of **16**

Complexation Studies of Hosts **16–18** *with Bipyridinium Dications.*—The new host molecules **16–18** contain two cavities for possible guest inclusion, the upper bowl-like cavity and a lower tetrameric benzo crown ether box-like hollow. Stoddart and co-workers[15] and more recently our group[16] have reported that simple bis(benzo crown ethers) and dibenzo crown ethers can complex the bipyridinium dications diquat (6,7-dihydrodipyrido[1,2-*a*;2′,1′-*c*]pyrazinediium) **24** and paraquat (1,1′-dimethyl-4,4′-bipyridinium) **25**. In addition Schneider *et al.*[17] have shown that compound **8** can bind quaternary ammonium cations in aqueous alkaline solutions. It was of interest therefore to investigate the solution complexation properties of hosts **16–18**, with **24** and **25** to elucidate whether inclusion complexation takes place, and if so in which cavity the guest is bound.

High-field ^{1}H NMR spectroscopy was used to study the binding of compounds **24** and **25** by hosts **16–18** in CD_3CN–$CDCl_3$ (1:1). Table 3 reports the significant large upfield shifts for all the bipyridyl protons of the diquat dicationic guest **24** upon complexation. The signals of the bipyridyl protons in the absence and presence of host **16** are shown in Fig. 5(*a*) and (*b*) respectively. Smaller upfield shifts of the OCH_2 crown ether protons ($\leqslant$0.07 ppm) of each host were also observed. Using nuclear Overhauser effect (NOE) difference spectroscopy,[18] irradiation of the $(N^+CH_2)_2$, 4,4′ or 5,5′ protons of **24** resulted in small but significant changes in the intensities of the crown OCH_2 proton absorptions of hosts **16–18**, suggesting that the $(N^+CH_2)_2$ protons are involved in weak C–H · · · O hydrogen bonding with the oxygen-donor atoms of the respective benzo crown ether moieties. Under identical experimental conditions, *no* shifts were observed with model host **11** containing no benzo crown subunits. These experimental findings suggest that the planar dicationic guest **24** binds in the lower benzo crown ether box-like cavity, intercalating between the electron-rich benzo crown ether subunits of the respective host **16–18**. Fig. 6 illustrates a possible solution-state geometry of interaction between **24** and the respective host which accounts for the ^{1}H NMR signals of the bipyridyl protons of **24** being shielded by the anisotropic ring currents of the aromatic rings of the four benzo-15-crown-5 units and also allows the possibility of electrostatic interactions between the pyridinium nitrogens and the crown ether oxygens. The work of Stoddart and co-workers[15] and ourselves[16] has already shown that the $(N^+CH_2)_2$ groups of **24** interact with the oxygen-donor atoms of simple dibenzo crown ethers and bis (crown ethers). Further stoichiometric additions of compound **24** to NMR solutions of **16–18** gave no evidence of its inclusion in the upper bowl-like cavity of each host.

Table 3 Proton NMR chemical shift differences (Δδ) for the diquat guest **24** upon complexation with hosts **16–18** in CD_3CN–$CHCl_3$ (1:1)

	δ				
	6,6′	4,4′	3,3′	5,5′	$(N^+CH_2)_2$
24	8.96	8.84	8.78	8.32	5.15
16–24	8.69	8.66	8.54	8.05	5.16
Δδ	−0.27	−0.18	−0.24	−0.27	+0.01
17–24	8.71	8.71	8.71	8.15	5.19
Δδ	−0.25	−0.13	−0.06	−0.17	+0.04
18–24	8.81	8.81	8.75	8.26	5.23
Δδ	−0.15	−0.03	−0.03	−0.06	−0.08

Table 4 Proton NMR chemical shift differences (Δδ) for the paraquat guest **25** upon complexation with hosts **16–18** in CD_3CN–$CHCl_3$ (1:1)

	δ		
	2,2′	3,3′	N^+Me
25	8.86	8.40	4.43
16–25	8.78	8.24	4.39
Δδ	−0.08	−0.16	−0.04
17–25	8.83	8.32	4.41
Δδ	−0.03	−0.08	−0.02
18–25	8.85	8.38	4.43
Δδ	−0.01	−0.02	0.00

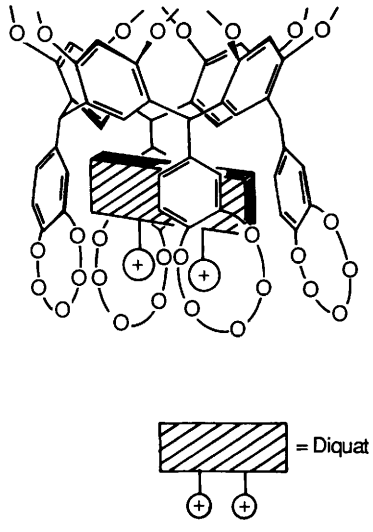

Fig. 6 Proposed solution host–guest structure of diquat **24** with crown ether hosts **16**, **17** or **18**

With the paraquat guest **25** significant upfield shifts of the bipyridyl protons were again observed with **16** and **17** (Table 4). However, very modest Δδ values (≤0.02 ppm) were obtained with the rigid cavitand host **18**. The results of NOE difference spectroscopic experiments with **25** implied weak interactions of this guest with the respective benzo crown ether moieties of **16** and **17**. Again no evidence for complexation between **25** and the model receptor **11** was observed, implying that compound **25** is also being included in the lower box-like cavity.

Comparing the results shown in Tables 3 and 4, it is noteworthy that the more rigid preorganised cavitand crown ether host molecule **18** shows a greater degree of selectivity for the diquat dication **24** over the paraquat guest **25** than do the more flexible hosts **16** and **17**.

The complexation of diquat **24** by **17** was also investigated using cyclic voltammetry. The addition of up to 5 equivalents of a concentrated solution of **24** in acetonitrile to the electrochemical solution of **17** had little effect on the reversible ferrocenecarboxyl oxidation wave of the host or the reversible diquat guest reduction waves ($\Delta E \leqslant 15$ mV). This suggests that the diquat dication, complexed at the benzo crown ether coordinating sites, is too far away to influence the electron density at the ferrocene iron atom, either inductively or through space.

Conclusion

The acid-catalysed condensation of 1,3-dihydroxybenzene and a redox-active or benzo crown ether functionalised aldehyde has been shown to be a general method for the simple preparation of a variety of novel multisite redox-active macrocyclic host molecules. The use of ferrocenecarbaldehyde **1** as a reactant and/or the subsequent acylation of the phenolic tetrameric macrocycles with chlorocarbonylferrocene **6** led to a range of redox-active molecules **4**, **5**, **7** and **12**.

The reaction of 1,3-dihydroxybenzene and 4-formylbenzo-15-crown-5 **13**, and subsequent benzoylation, ferrocenoylation or reaction with bromochloromethane gave host molecules **16–18** capable of binding the bipyridinium dications diquat **24** and paraquat **25** at the crown ether recognition sites. However the benzo-15-crown-5 binding site was found to be too remote to allow electrochemical detection of the complexation of diquat **24** by the ferrocenoylated host **17**.

Experimental

Solvent and Reagent Pre-treatment.—Where necessary, solvents were purified by distillation prior to use. The following drying agents and conditions were used before distillation: acetonitrile was distilled from CaH_2, dichloromethane from P_2O_5, hexane and diethyl ether from sodium, toluene and tetrahydrofuran (thf) from sodium using benzophenone as the indicator, dimethylformamide (dmf) under reduced pressure from $MgSO_4$ and thionyl chloride from triphenyl phosphite.

Unless otherwise stated, commercial grade chemicals were used without further purification. The octols **3**,[9] **8**,[4] **9**,[5] chlorocarbonylferrocene **6**,[11] 4-formylbenzo-15-crown-5 **13**[12] and the bipyridinium dications **24**[15] and **25**[15] were prepared according to the literature procedures.

Instrumental Methods.—Melting points were recorded on a Gallenkamp apparatus in open capillaries and are uncorrected. Infrared spectra were obtained on a Perkin-Elmer 297 instrument (4000–600 cm^{-1}) as KBr discs, nuclear magnetic resonance spectra on JEOL FX-90Q, GX-270 and Bruker WH400 instruments using tetramethylsilane as internal standard. Mass spectra and fast atom bombardment spectra were recorded on a Kratos MS80 RF mass spectrometer; the latter used an argon primary beam and 3-nitrobenzyl alcohol as the matrix. The UV/VIS spectra were recorded on a Shimadzu uv-240 spectrophotometer. All elemental analyses were performed at the University of Birmingham.

Electrochemical Measurements.—Cyclic voltammetry, differential pulse voltammetry and controlled-potential electrolysis were carried out with a PAR 174A potentiostat. All the electrochemical measurements were performed under nitrogen, and used $[NBu_4][BF_4]$ as the supporting electrolyte. The cyclic voltammetry and differential pulse voltammetry were carried out using a three-electrode cell, which incorporated a saturated calomel reference electrode, a platinum-wire auxiliary electrode and a platinum-bead working electrode. The current–voltage curves were recorded with a Philips X-Y recorder. During the controlled-potential electrolysis a large platinum-gauze electrode was placed in the main cell compartment containing the stirred test solution. The counter electrode was another large platinum-gauze square, held in a secondary cell compartment isolated by a sintered-glass disc. The current passed was measured using a Hi-tek electronic integrator, which was

calibrated in conjunction with the cell using a known amount of ferrocene.

Syntheses.—2,8,14,20-*Tetraferrocenylpentacyclo*-[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]*octacosa*-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaen*-4,6,10,12,16,18,22,24-*octapropanoic acid* **4**. A mixture of octol **3** (1.0 g, 0.82 mmol), pyridine (0.5 cm^3, 6.0 mmol) and propionic anhydride (5 cm^3, 37 mmol) was stirred at 110 °C for 1.25 h. The reaction flask was then stored at 0 °C overnight and the product **4** was collected as a brown precipitate by filtration, 1.13 g (83% overall yield for the preparation of the octol and subsequent propionylation), m.p. >250 °C, *m/z* 1673, IR 1760 cm^{-1} (C=O stretch). NMR ($CDCl_3$): ^{1}H, δ 1.20 (24 H, t, *J* 5.3, CH_3), 2.42 (16 H, q, *J* 5.3 Hz, CH_2), 3.78 (8 H, br s, ferrocenyl H), 3.97 (20 H, s, ferrocenyl H), 4.09 (8 H, br s, ferrocenyl H), 5.21 (4 H, s, CH) and 6.21 (4 H, s, aryl H); ^{13}C, δ 8.97 (CH_3), 27.67 (CH_2), 37.00 (CH), 68.09, 68.67 (ferrocenyl C), 90.23 (ferrocenyl C, *ipso*), 115.33, 130.16, 131.66, 145.96 (aryl C) and 171.88 (C=O) (Found: C, 64.9; H, 5.0. Calc. for $C_{92}H_{88}Fe_4O_{16}$: C, 66.0, H, 5.3%).

2,8,14,20-*Tetraferrocenylpentacyclo*[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]-*octacosa*-1(25)3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaen*-4,6,10,12,16,18,22,24-*octabenzoic acid* **5**. A mixture of octol **3** (1.22 g, 1 mmol) triethyamine (1.5 cm^3, 10 mmol), 4-dimethylaminopyridine (0.33 g, 0.25 mmol) and benzoyl chloride (2.8 g, 20 mmol) in thf (100 cm^3) was stirred under nitrogen at reflux for 112 h. This slurry was then rotary evaporated to dryness and the black residue extracted with dichloromethane. The resulting orange-brown solution was washed with water, dried over $MgSO_4$, filtered and rotary evaporated to a brown oil. The product was purified by column chromatography on alumina with diethyl ether–dichloromethane (75:25 v/v) as the eluent to give compound **5** as orange crystals (0.21 g, 10% overall yield for the preparation of the octol and subsequent benzoylation), m.p. >250 °C, *m/z* 2057, IR 1735 cm^{-1} (C=O stretch). NMR ($CDCl_3$): ^{1}H, δ 3.93 (24 H, s, ferrocenyl H), 4.05 (4 H, s, ferrocenyl H), 4.12 (4 H, s, ferrocenyl H), 4.23 (4 H, s, ferrocenyl H), 5.65 (4 H, s, CH), 6.64 (2 H, s, aryl H), 6.72, 6.74 (4 H, 2 × s, aryl H), 7.20 (8 H, t, *J* 7.6, aryl H), 7.42 (12 H, t, *J* 7.4, aryl H), 7.58 (4 H, t, *J* 7.1, aryl H), 7.85 (16 H, q, *J* 7.6 Hz, aryl H) and 8.00 (2 H, s, aryl H). ^{13}C, δ 37.20 (CH), 67.09, 67.98, 68.51, 69.06 (ferrocenyl C), 89.94 (ferrocenyl C, *ipso*), 114.82, 116.47, 128.24, 129.88, 130.35, 131.15, 133.14, 133.90, 145.57, 147.17 (aryl C), 163.30 and 164.70 (C=O) (Found: C, 72.4; H, 4.4. Calc. for $C_{124}H_{88}Fe_4O_{16}$: C, 72.3; H, 4.3%).

2,8,14,20-*Tetraferrocenyl*-4,6,10,12,16,18,22,24-*octa*(*ferrocenecarbonyloxy*)*pentacyclo*[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]*octacosa*-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaene* **7**. To a refluxing mixture of octol **3** (0.17 g, 0.14 mmol), triethylamine (0.6 cm^3, 4 mmol), and 4-dimethylaminopyridine (0.03 g, 0.25 mmol) in thf (75 cm^3) under nitrogen was added dropwise a solution of chlorocarbonylferrocene **6** (0.7 g, 2.8 mmol) in thf (75 cm^3). This black slurry was refluxed for 27 h, before being rotary evaporated to dryness and the residue extracted with dichloromethane. The orange-brown solution was washed with water, dried over $MgSO_4$, and rotary evaporated to give a brown oil. This residue was purified by column chromatography on alumina with diethyl ether–dichloromethane (90:10 v/v) as the eluent to give compound **7** as small orange-red crystals (0.04 g, 10% overall yield for the preparation of the octol and subsequent ferrocenoylation), m.p. >250 °C, *m/z* 2921, IR 1720 cm^{-1} (C=O stretch). NMR ($CDCl_3$): ^{1}H, δ 3.80 (20 H, br s, ferrocenyl H), 4.19 (56 H, s, ferrocenyl H), 4.38 (16 H, s, ferrocenyl H), 4.82 (16 H, br s, ferrocenyl H), 5.48 (4 H, s, CH) and 6.72 (4 H, s, aryl H); ^{13}C, δ 29.72 (CH), 69.32, 69.75, 70.14, 70.53, 70.66, 70.82, 71.24 (ferrocenyl C), 89.95 (ferrocenyl C, *ipso*), 112.93, 128.27, 130.03, 132.37 (aryl C) and 172.17 (C=O) (Found: C, 63.2; H, 5.1. Calc. for $C_{156}H_{120}Fe_{12}O_{16}$: C, 64.1; H, 4.1%).

2,8,14,20-*Tetramethylpentacyclo*[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]-*octacosa*-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaen*-4,6,10,12,16,18,22,24-*octabenzoic acid* **10**. The procedure for the preparation of compound **10** followed that described for **5**, using octol **8**, except that the period of reflux was reduced to 8 h. The product was purified by column chromatography on alumina with dichloromethane as the eluent to give **10** as a white powder (0.70 g, 51% overall yield), m.p. >250 °C, *m/z* 1379, IR 1740 cm^{-1} (C=O stretch). NMR ($CDCl_3$): ^{1}H, δ 1.64 (12 H, d, *J* 7.1, CH_3), 4.65 (4 H, q, *J* 7.0 Hz, CH), 6.49 (2 H, s, aryl H), 7.09, 7.21 (4 H, 2 × s, aryl H), 7.31–7.42 (16 H, m, aryl H), 7.55, 7.57 (8 H, 2 × s, aryl H), 7.68 (2 H, s, aryl H) and 7.77–7.87 (16 H, m, aryl H). ^{13}C, δ 20.39 (CH_3), 32.42 (CH), 116.01, 117.77, 125.77, 126.42, 128.40, 129.09, 130.06, 132.70, 133.41, 136.53, 145.93, 147.78 (aryl C) and 164.20 (C=O) (Found: C, 76.4; H, 4.9. Calc. for $C_{88}H_{64}O_{16}$: C, 76.7; H, 4.7%).

2,8,14,20-*Tetraphenylpentacyclo*[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]-*octacosa*-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaen*-4,6,10,12,16,18,22,24-*octabenzoic acid* **11**. The procedure for the preparation of compound **11** followed that described for **5**, using octol **9**, except that the reflux time was reduced to 12 h. The product was purified by column chromatography on alumina with dichloromethane as the eluent to give **11** as a white powder (0.56 g, 34% overall yield), m.p. >250 °C, *m/z* 1627, IR 1735 cm^{-1} (C=O stretch). NMR ($CDCl_3$): ^{1}H, δ 5.75 (4 H, s, CH), 6.22 (2 H, s, aryl H), 6.67 (2 H, s, aryl H), 6.76, 6.79 (8 H, 2 × s, aryl H), 7.04 (12 H, br s, aryl H), 7.18–7.30 (18 H, m, aryl H), 7.41–7.50 (10 H, m, aryl H), 7.54, 7.55, 7.57 (8 H, 3 × s, aryl H), 7.69, 7.70 and 7.72 (8 H, 3 × s, aryl H); ^{13}C, δ 45.13 (CH), 117.09, 126.45, 128.18, 128.34, 128.86, 129.44, 129.83, 130.06, 131.36, 132.01, 132.96, 133.28, 140.40, 147.36 (aryl C), 163.29 and 164.07 (C=O) (Found: C, 79.1; H, 4.4. Calc. for $C_{108}H_{72}O_{16}$: C, 79.8; H, 4.5%).

4,6,10,12,16,18,22,24-*Octa*(*ferrocenecarbonyloxy*)-2,8,14,20-*tetramethylpentacyclo*[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]*octacosa*-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaene* **12**. The procedure for the preparation of compound **12** followed that described for **7**, using octol **8**, except that the reflux time was reduced to 2 h. The product was purified by column chromatography on alumina using dichloromethane–methanol (99.75:0.25 v/v) as the eluent to give **12** as orange crystals (0.10 g, 33% overall yield), m.p. >250 °C, *m/z* 2241, IR 1725 cm^{-1} (C=O stretch). NMR ($CDCl_3$): ^{1}H, δ 1.65 (12 H, d, *J* 7.0, CH_3), 4.23 (40 H, s, ferrocenyl H), 4.43 (16 H, s, ferrocenyl H), 4.65 (4 H, q, *J* 7.0 Hz, CH), 4.71 (4 H, s, ferrocenyl H), 4.76 (4 H, s ferrocenyl H), 4.83 (4 H, s, ferrocenyl H), 4.94 (4 H, s, ferrocenyl H), 6.34 (2 H, s, aryl H), 7.06, 7.14 (4 H, 2 × s, aryl H) and 7.65 (2 H, s, aryl H); ^{13}C, δ 20.58 (CH_3), 32.03 (CH), 69.83, 70.39, 71.58, 71.65 (ferrocenyl C), 115.56, 116.41, 125.87, 132.51, 135.83, 145.88, 147.89 (aryl C), 169.18 and 169.68 (C=O) (Found: C, 63.5; H, 4.4. Calc. for $C_{120}H_{96}Fe_8O_{16}$: C, 64.3; H, 4.3%).

2,8,14,20-*Tetrakis*(2,3,5,6,8,9,11,12-*octahydro*-1,4,7,10,13-*benzopentaoxacyclopentadecin*-15-*yl*)*pentacyclo*-[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]*octacosa*-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaen*-4,6,10,12,16,18,22,24-*octol* **14**. This compound was prepared using a procedure analogous to that employed for **8**, from 1,3-dihydroxybenzene **2** and 4′-formylbenzo-15-crown-5 **13**. The product was isolated as a fawn powder (7.61 g), m.p. >250 °C, IR 3700–2500 (hydrogen-bonded OH), 2950–2850 cm^{-1} (saturated C–H stretch). This material was used without further purification in subsequent reactions.

2,8,14,20-*Tetrakis*(2,3,5,6,8,9,11,12-*octahydro*-1,4,7,10,13-*benzopentaoxacyclopentadecin*-15-*yl*)*pentacyclo*-[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]*octacosa*-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaen*-4,6,10,12,16,18,22,24-*octapropanoic acid* **15**. The procedure for the preparation of compound **15** followed that described for **4**, using octol **14**. The product was purified by column chromatography on alumina using dichloromethane–methanol (95:5 v/v) as the eluent to give **15** as a cream powder (0.71 g, 43% overall yield), m.p. 155–158 °C,

m/z 2001, IR 1760 (C=O stretch), 2950–2850 cm^{-1} (saturated C–H stretch). NMR ($CDCl_3$): ^1H, δ 1.03 (24 H, t, *J* 5.3, CH_3), 2.33 (16 H, q, *J* 5.3 Hz, CH_2), 3.74, 3.83, 4.07 (64 H, 3 × s, OCH_2CH_2O), 5.45 (4 H, s, CH), 6.22 (12 H, s, aryl H), 6.53 (4 H, 2 × s, aryl H), 6.87 and 6.91 (4 H, 2 × s, aryl H); ^{13}C, δ 9.01 (CH_3), 27.38, 29.72 (CH_2), 43.99 (CH), 69.06, 69.84, 70.62, 70.98 (OCH_2CH_2O), 115.10, 116.24, 122.13, 131.72, 132.18, 132.92, 146.68, 147.72, 147.75, 148.79 (aryl C), 171.49 and 172.20 (C=O) (Found: C, 63.9; H, 6.8. Calc. for $C_{108}H_{128}O_{36}$: C, 64.8; H, 6.4%).

2,8,14,20-*Tetrakis*(2,3,5,6,8,9,11,12-*octahydro*-1,4,7,10,13-*benzopentaoxacyclopentadecin*-15-*yl*)*pentacyclo*-[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]*octacosa*-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaen*-4,6,10,12,16,18,22,24-*octabenzoic acid* **16**. The procedure for the preparation of compound **16** followed that described for **5**, using octol **14**, except that the reflux time was reduced to 12 h. The product was purified by filtering the final dichloromethane solution through a bed of Celite before eluting the residue from the filtrate down an alumina column using dichloromethane–methanol (98:2 v/v) as the mobile phase to give **16** as a white powder (0.50 g, 21% overall yield), m.p. >250 °C, *m/z* 2387, IR 1735 (C=O stretch), 2950–2850 cm^{-1} (saturated C–H stretch). NMR ($CDCl_3$): ^1H, δ 3.58, 3.63, 3.65, 3.70, 3.81, 3.97 (64 H, 6 × s, OCH_2CH_2O), 5.71 (4 H, s, CH), 6.28 (4 H, s, aryl H), 6.33 (2 H, s, aryl H), 6.43, 6.45 (4 H, 2 × s, aryl H), 6.54 (2 H, s, aryl H), 6.62 (2 H, s, aryl H), 6.97 (2 H, s, aryl H), 7.28–7.55 (28 H, m, aryl H), 7.68, 7.70 (8 H, 2 × s, aryl H), 7.84 and 7.87 (8 H, 2 × s, aryl H); ^{13}C, δ 44.64 (CH), 68.51, 69.06, 69.39, 69.81, 70.53, 70.95, (OCH_2CH_2O), 114.13, 115.04, 116.96, 117.54, 122.36, 127.72, 128.37, 128.53, 128.76, 129.15, 129.83, 130.26, 131.85, 132.31, 133.02, 133.28, 133.90, 146.97, 147.43, 147.82, 148.82 (aryl C), 163.13 and 164.43 (C=O) (Found: C, 69.4; H, 5.2. Calc. for $C_{140}H_{128}O_{36}$: C, 70.5; H, 5.4%).

4,6,10,12,16,18,22,24-*Octa*(*ferrocenecarbonyloxy*)-2,8,14,20-*tetrakis*(2,3,5,6,8,9,11,12-*octahydro*-1,4,7,10,13-*benzopentaoxacyclopentadecin*-15-*yl*)*pentacyclo*[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]-*octacosa*-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-*dodecaene* **17**. The procedure for the preparation of compound **17** followed that described for **7**, using octol **14**, except that the reflux time was reduced to 2 h. The product was purified by column chromatography on alumina using dichloromethane–methanol (99.25:0.75 v/v), m.p. 131–134.5 °C, *m/z* 3250, IR 1730 (C=O stretch), 2950–2850 cm^{-1} (saturated C–H stretch). NMR ($CDCl_3$): ^1H, δ 3.67–3.82 (56 H, m, OCH_2CH_2O), 4.03 (20 H, s, ferrocenyl H), 4.07, 4.13 (8 H, 2 × s, OCH_2CH_2O), 4.20 (20 H, s, ferrocenyl H), 4.33, 4.35 (8 H, 2 × s, ferrocenyl H), 4.43 (8 H, s, ferrocenyl H), 4.54 (4 H, s, ferrocenyl H), 4.66 (4 H, s, ferrocenyl H), 4.72 (4 H, s, ferrocenyl H), 4.82 (4 H, s, ferrocenyl H), 5.74 (4 H, s, CH), 6.35–6.37 (8 H, m, aryl H), 6.44, 6.48 (4 H, 2 × s, aryl H), 6.56, 6.58 (4 H, 2 × s, aryl H), 7.30 and 7.32 (4 H, 2 × s, aryl H); ^{13}C, δ 44.03, 44.08 (CH), 68.67, 69.04, 69.35, 69.52, 69.57, 69.72, 69.79, 69.98, 70.08, 70.14, 70.21, 70.33, 70.49, 70.86, 70.94, 71.03, 71.48, 71.88, 72.19 (OCH_2-CH_2O and ferrocenyl C), 114.11, 115.23, 116.09, 122.00, 131.19, 132.25, 132.85, 146.84, 147.28, 147.59, 148.77 (aryl C), 168.27 and 169.68 (C=O) (Found: C, 63.3; H, 5.3. Calc. for C_{172}-$H_{160}Fe_8O_{36}$: C, 63.6; H, 5.0%).

1,21,23,25-*Tetrakis*(2,3,5,6,8,9,11,12-*octahydro*-1,4,7,10,13-*benzopentaoxacyclopentadecin*-15-*yl*)-2,20:3,19-*dimetheno*-1H,21H,23H,25H-*bis*[1,3]*dioxocino*[5,4,i:5′,4′-i′]-*benzo*-[1,2-d:5,4-d′]*bis*[1,3]*benzodioxocin* **18**. To a mixture of compound **14** (9.20 g, 5 mmol) and anhydrous potassium carbonate (8.00 g, 58 mmol) in dmf (150 cm^3) was added bromochloromethane (4.00 g, 31 mmol). This slurry was stirred under nitrogen at 85 °C for 68 h. The mixture was rotary evaporated to dryness, and the residue triturated in dichloromethane (100 cm^3). The suspension was filtered through a bed of Celite, and the bed washed thoroughly with dichloromethane (500 cm^3). The combined washings were dried over $MgSO_4$, filtered and rotary evaporated to dryness. The product was purified by column chromatography on alumina with dichloromethane–methanol (95:5 v/v) as the mobile phase. The eluent was rotary evaporated to dryness, and the residue was redissolved in dichloromethane before several large spatulas of decolourising charcoal were added. This slurry was filtered through a bed of Celite, and the filtrate was washed with water and dried over $MgSO_4$. The mixture was then filtered, rotary evaporated to dryness, and the residue was triturated in diethyl ether to give compound **18** as a cream solid after a final filtration (0.32 g, 4% overall yield), m.p. >250 °C, *m/z* 1602, IR 3000–2700 cm^{-1} (saturated C–H stretch). NMR ($CDCl_3$): ^1H, δ 3.75–3.76 (32 H, m, OCH_2CH_2O), 3.86–3.89 (16 H, m, OCH_2CH_2O), 3.99–4.01 (8 H, m, OCH_2CH_2O), 4.12–4.14 (8 H, m, OCH_2CH_2O), 4.58 (4 H, d, *J* 7.1, inner OCH_2O), 5.85 (4 H, d, *J* 7.1 Hz, outer OCH_2O), 6.30 (4 H, s, CH), 6.66 (4 H, s, aryl H), 6.71 (4 H, s, aryl H), 6.86 (8 H, s, aryl H) and 7.12 (4 H, s, aryl H); ^{13}C, δ 41.10 (CH), 68.77, 69.36, 69.71, 70.59, 71.14 (OCH_2CH_2O), 99.63 (OCH_2O), 113.28, 115.85, 116.60, 121.32, 126.81, 132.18, 137.83, 147.95, 148.86 and 155.72 (aryl C) (Found: C, 65.9; H, 6.3. Calc. for $C_{88}H_{96}O_{28}$: C, 66.0; H, 6.0%).

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