Pergamon

Tetrahedron Letters, Vol. 35, No. 27, pp. 4835-4838, 1994
Elsevier Science Ltd
Printed in Great Britain
0040-4039/94 $7.00+0.00

0040-4039(94)00889-2

An Optically-Active [2]Catenane Made to Order

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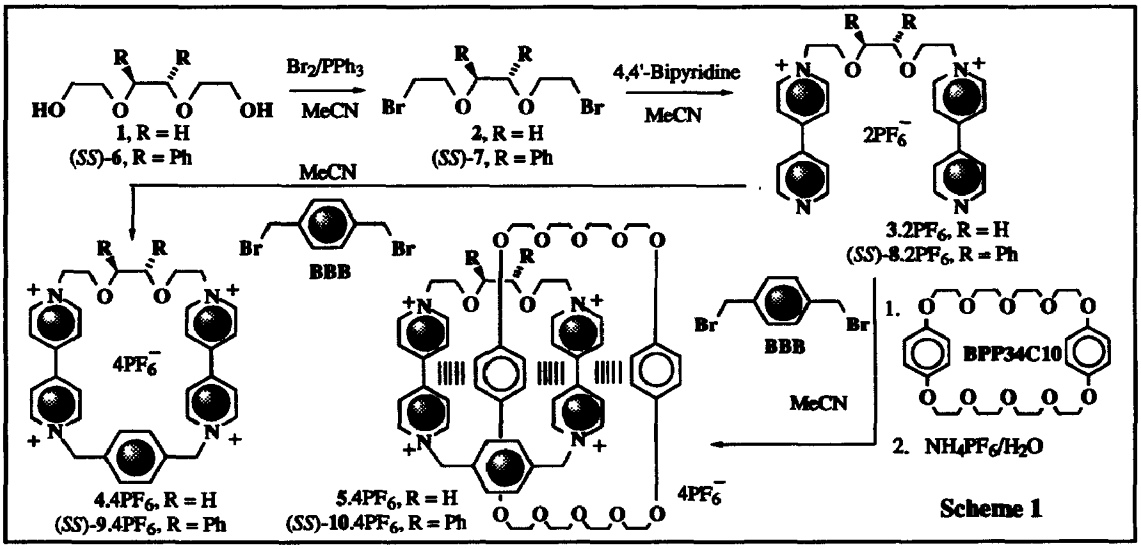
Abstract: The self-assembly of an optically-active [2]catenane, incorporating a chiral hydrobenzoin unit in one of its component rings, has been achieved.

Recently, we have shown[1] that catenanes[2,3] and rotaxanes[2,4] may be self-assembled[1-5] from molecular components containing π-electron rich and deficient aromatic units. In all cases, the π-electron deficient units have comprised 4,4'-bipyridinium residues within the rigid tetracationic cyclophanes, cyclobis(paraquat-*p*-phenylene)[6] and cyclobis(paraquat-4,4'-biphenylene).[3] Here, we report that one of the paraxylyl groups[7] in the former may be replaced by a flexible $-CH_2CH_2OCH_2CH_2OCH_2CH_2-$ chain, without impeding catenane formation. This observation provides the basis for introducing chirality in the form of (*SS*)-hydrobenzoin residues[8] into the central bismethylenedioxy unit of the flexible spacer, permitting the self-assembly (**Scheme 1**) of an optically-active [2]catenane.[9]

The salt **3**.2PF_6, which can be prepared[10] in two steps (**1**–>**2**–>**3**.2PF_6) starting from **1**, reacts in MeCN with 1,4-bis(bromomethyl)benzene (**BBB**) to afford[10] **4**.4PF_6, and, in the presence of bisparaphenylene-34-crown-10 (**BPP34C10**), to give[10] the [2]catenane **5**.4PF_6. The cyclophane (*SS*)-**9**.4PF_6 and the [2]catenane (*SS*)-**10**.4PF_6 have been synthesised[11] in an analogous fashion from the salt (*SS*)-**8**.2PF_6, obtained[11] in two steps [(*SS*)-**6**–>(*SS*)-**7**–>(*SS*)-**8**.PF_6] from (*SS*)-**6**.



Scheme 1

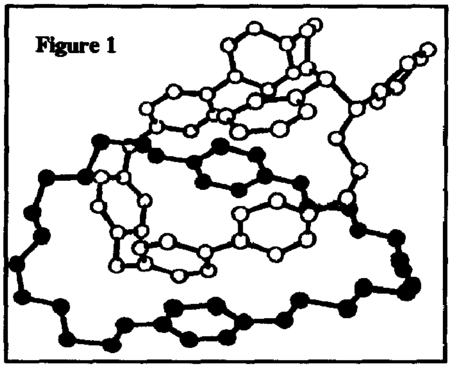


Figure 1

The X-ray structural analysis[12] of (*SS*)-**10**.$4PF_6$ reveals (**Fig. 1**) that the **BPP34C10** macrocycle is threaded through the centre of the tetracationic cyclophane (*SS*)-9^{4+}, with one of the π-electron donating hydroquinol rings sandwiched between the π-electron accepting bipyridinium units of (*SS*)-9^{4+}. In common with the [2]catenane[2,3] comprised of **BPP34C10** and cyclobis(paraquat-*p*-phenylene), the 'inside' and 'alongside' hydroquinol rings display an in-plane rotation with respect to each other of *ca.* 20° in the **BPP34C10** component. In contrast, the two bipyridinium units are also sheared by *ca.* 10° in the (*SS*)-9^{4+} component. Both the bipyridinium and paraphenylene units display bowing, with the paraxylylene $C-CH_2$ bonds subtending an angle of 10° and the 'inside' and 'alongside' bipyridinium N^+-CH_2 bonds subtending angles of 26° and 14°, respectively. In addition, there is appreciable twisting of both the 'inside' (*ca.* 10°) and 'alongside' (*ca.* 36°) bipyridinium units. The mean interplanar separation of the hydroquinol rings is 6.9Å. The introduction of the chiral spacer unit results in a splaying of the bipyridinium units with respect to each other with the 'corner' CH_2 groups being separated by 5.8Å in the case of the paraxylylene unit and by 7.3Å in the case of the $-CH_2CH_2OCHPhCHPhOCH_2CH_2-$ unit[13] within which the phenyl (Ph) groups adopt an antiperiplanar geometry. Despite these structural distortions, the compound still displays a strong charge-transfer band (*cf.* λ_{max} = 462 nm in MeCN solution), reflecting the π/π-stacking between the donors and the acceptors. The solid state structure also displays an additional 'T-type' interaction between the electropositive H atoms on the 'inside' hydroquinol ring and the orthogonally-oriented paraphenylene π-system (centroid-centroid separation = 5.1Å). In contrast with related catenanes[2,3], there are no continuously stacked π-donor/π-acceptor arrays in the solid state. This absence of stacking could be a consequence of accommodating the bulky Ph substituents within the crystal lattice.

Table 1. ^1H NMR Chemical shift data [δ values] for **5**.$4PF_6$ in CD_3COCD_3 (400 MHz) at +20°C and at −60°C

	CH				Polyether chain			OCH_2
	α	β	C_6H_4	CH_2N^+	CH_2N^+	CH_2O	OC_6H_4O	$\alpha, \beta, \gamma, \delta$
5.$4PF_6$ [a]	9.37 8.99	8.24 8.17	8.09	6.10	4.97	4.12	6.21 [b]	3.36-3.91 [c]
5.$4PF_6$ [d]	9.49 [e] 9.33 [e] 9.08 8.90	8.38 8.23 8.23 8.23	8.12	6.11 [f] 6.03 [f]	4.95	3.94	6.16 [g]	3.30-4.20 [h]

[a] Recorded at +20°C. [b] Although the signal for the protons on the 'inside' hydroquinol ring is not visible at +20°C, saturation transfer occurs at −10°C when the signal for the 'alongside' hydroquinol ring protons is irradiated at δ 6.21, indicating δ values for the 'inside' hydroquinol ring protons of 4.40 and 5.38. [c] This broad multiplet includes signals for the OCH_2CH_2O protons in the tetracationic cyclophane component of the [2]catenane. [d] Recorded at −60°C. [e] The $\delta\nu$ value of 63 Hz between these two signals has been used to obtain a value of 140 s^{-1} for k from the approximate expression $k = [\pi(\delta\nu)]^{-1/2}$. The Eyring equation was used to calculate a $\Delta G^‡$ value of 11.5 kcal mol^{-1} at the coalescence temperature of −33°C. [f] The $\Delta\nu$ value of 31 Hz between these two signals has been used to obtain a value of 69 s^{-1} for k which gives a $\Delta G^‡$ value of 11.7 kcal mol^{-1} at the coalescence temperature of −37°C. [g] This is the signal for the 'alongside' hydroquinol ring protons. An additional signal is observed at δ 5.55 for two of the 'inside' hydroquinol ring protons. [h] The series of multiplets in this region of the spectrum includes signals for the OCH_2CH_2O protons in the tetracationic cyclophane component of the [2]catenane as well as a signal for the other two 'inside' hydroquinol ring protons.

Table 2. ^{1}H NMR Chemical shift data [δ values] for (*SS*)-**10**.4PF_6 in CD_3COCD_3 (400 MHz) at +20°C

	CH		C_6H_4	Ph	OC_6H_4O	CH_2N^+	PhCH	Polyether chain		OCH_2
	α	β						CH_2N^+	CH_2O	α, β, γ, δ
(*SS*)-**10**.4PF_6	9.39	8.24	8.10	7.40[a]	6.18[b]	6.13	5.14	4.84[a,c]	4.32[a,c]	3.25[a]
	8.51	8.15		7.59[a]		6.08		4.32[a,c]	3.70[a,c]	4.00[a]

[a] The values relate to the ranges over which signals are observed. [b] This is the signal for the 'alongside' hydroquinol ring protons. The signals for the 'inside' hydroquinol ring protons are not observed at +20°C. [c] These signals, which have been assigned as a result of a COSY45 experiment performed over this region of the spectrum, form an ABCD system.

Both (*SS*)-**10**.4PF_6 and its achiral counterpart **5**.4PF_6 exhibit temperature dependencies in their ^{1}H NMR spectra recorded in CD_3COCD_3. The chemical shift data listed in **Table 1** shows the presence of two different circumrotation processes whereby both hydroquinol rings can occupy the inside region of the tetracationic cyclophane and both bipyridinium units can occupy the inner portion of **BPP34C10**. Equilibration of the latter type in a degenerate sense is associated with a free energy barrier of *ca.* 11.6 kcal mol^{-1}. The other degenerate equilibration process is clearly associated with a much higher free energy of activation as indicated by the different ^{1}H NMR signal observed for the hydroquinol ring protons in **5**.4PF_6 at +20°C. The chemical shift data presented in **Table 2** support the view that the dynamic situation for (*SS*)-**10**.4PF_6 in CD_3COCD_3 solution is quantitatively similar to that for **5**.4PF_6. However, the presence of chirality in (*SS*)-**10**.4PF_6 results in highly disperse spectra at low temperatures, reflecting the expected nonequivalences of all the protons in the molecule when both circumrotation processes are slow on the ^{1}H NMR time-scale.

The self-assembly of (*SS*)-**10**.4PF_6 has implications for the future design of chiral solid-state devices and in the construction of asymmetric catalysts.

Acknowledgements. We are grateful to the Science and Engineering Research Council in the UK and to the Ministerio de Educacíon y Ciencia in Spain for the support of this research programme.

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7. When both paraxylyl residues in cyclobis(paraquat-*p*-phenylene) are replaced by $-CH_2CH_2OCH_2CH_2OCH_2CH_2O-$ chains, the resulting tetracationic cyclophane loses its ability to complex π-electron rich aromatic substrates.
8. (*SS*)-Hydrobenzoin is readily available from the osmium-catalysed asymmetric dihydroxylation of *trans*-stilbene. See J.S.M. Wai, I. Markó, J.S. Svendsen, M.G. Finn, E.N. Jacobsen, K.B. Sharpless, *J. Am. Chem. Soc.* **1989**, *111*, 1123-1125.
9. Recently, optically-active catenanes incorporating heptakis(2,6-di-*O*-methyl)-β-cyclodextrin have been self-assembled and characterised (D. Armspach, P.R. Ashton, C.P. Moore, N. Spencer, J.F. Stoddart, T.J. Wear, D.J. Williams, *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 854-858). These catenated cyclodextrins rely on the use of a natural product to provide the source of chirality. Also, optically-active copper (I) catenates have been resolved by chiral HPLC by J.-C. Chambron, D.K. Mitchell, J.-P. Sauvage, *J. Am. Chem. Soc.* **1992**, *114*, 4625-4631; Y. Kaida, Y. Okamoto, J.-C. Chambron, D.K.Mitchell, J.-P. Sauvage, *Tetrahedron Lett.* **1993**, 1019-1023. For an excellent review on topologically-chiral catenanes and knots, see J.-C. Chambron, C. Dietrich-Buchecker, J.-P. Sauvage, *Top. Curr. Chem.* **1993**, *165*, 131-162. For an early discussion on the incorporation of chirality into catenanes, see G. Schill, *Catenanes, Rotaxanes and Knots*, Academic Press, New York, 1971.

10. Preparation and characterisation of (*a*) 3.2PF_6, (*b*) 4.4PF_6 and (*c*) 5.4PF_6: (*a*) 3.2PF_6: 4,4'-Bipyridine (11.7 g, 75 mmol) and 1,8-dibromo-3,6-dioxaoctane (2) (4.17 g, 15 mmol) were dissolved in dry MeCN (100 mL) and the reaction mixture was heated under reflux for 2 days in an inert atmosphere. The precipitate which formed was filtered off, washed with MeCN and Et_2O and dissolved in H_2O (150 mL). The aqueous solution was washed with Et_2O (4 x 40 mL) before being concentrated to give a residue which was subjected to column chromatography [Al_2O_3:H_2O/i-PrOH (1:4)]. The residue remaining after removal of the solvent was dissolved in H_2O and treated with an aqueous NH_4PF_6 solution. The colourless precipitate was filtered off, washed (H_2O then MeOH then Et_2O) and dried. Extraction with acetone afforded a crystalline residue which was recrystallised from Me_2CO-MeOH to give 3.2PF_6 (7.83 g, 72%), m.p. 159-161°C; FABMS: m/z = 573 $(M-PF_6)^+$; ^{1}H NMR (CD_3CN): δ = 3.53 (s, 4H), 3.86 (t, 4H), 4.64 (t, 4H), 7.69-7.73 (m, 4H), 8.22-8.27 (m, 4H), 8.69-8.73 (m, 4H), 8.75-8.79 (m, 4H). (*b*) 4.4PF_6: 3.2PF_6 (0.72 g, 1.0 mmol) and 1,4-bis(bromomethyl)benzene (**BBB**) (0.36 g, 1.4 mmol) were reacted in refluxing MeCN (150 mL) for 42 h. The solvent was evaporated off and the residue which was dissolved in $MeNO_2$ was treated with Et_4NCl. The precipitate was filtered off and subjected to column chromatography [SiO_2:MeOH/H_2O/satd aq NH_4Cl (6:3:1)]. The fractions containing the product were combined, evaporated to dryness, redissolved in H_2O and treated with a saturated aqueous NH_4PF_6 solution. The white precipitate was filtered off, dried, and recrystallised from Me_2CO–H_2O to afford 4.4PF_6 (430 mg, 40%), m.p. > 286°C (decomp); FABMS: m/z = 967 $(M\text{-}PF_6)^+$; ^{1}HNMR (CD_3CN): δ = 3.38 (s, 4H), 3.82 (t, 4H), 4.69 (t, 4H), 5.87 (s, 4H), 7.60 (s, 4H), 8.19-8.22 (m, 4H), 8.22-8.26 (m, 4H), 8.74-8.78 (m, 4H), 8.88-8.92 (m, 4H). Crystals suitable for X-ray crystallography were grown by vapour diffusion of i-Pr_2O into a $MeNO_2$ solution of 4.4PF_6. Crystal data for 4.4PF_6: 2$MeNO_2$.H_2O: triclinic, a = 10.239(4), b = 12.159(5), c = 23.114(10) Å, α = 98.98(4), β = 94.71 Å, γ = 108.19(3)°, V = 2764 Å^3, space group $P\bar{1}$, Z = 2, ρ = 1.53 g cm^{-3}, 5825 independent observed reflections with [$|F_o| > 3\sigma(|F_o|)$, $2\theta \le 116°$] refined anisotropically to R = 0.087, R_w = 0.090. (*c*) 5.4PF_6: **BPP34C10** (280 mg, 0.52 mmol) and 3.2PF_6 (142 mg, 0.20 mmol) were dissolved in MeCN (20 mL) and **BBB** (56 mg, 0.21 mmol) was added. The solution was stirred at room temperature for 3 days. The solvent was evaporated off and the residue was redissolved in H_2O and washed with $CHCl_3$. The aqueous layer was treated with a saturated aqueous solution of NH_4PF_6 and the precipitate which formed was collected by filtration. The precipitate was recrystallised twice from MeCN–H_2O to give 5.4PF_6 as an orange-red solid (160 mg, 49%); FABMS: m/z = 1503 $(M-PF_6)^+$.
11. Preparation and characterisation of (*a*) (*SS*)-7, (*b*) (*SS*)-8.2PF_6, (*c*) (*SS*)-9.4PF_6, and (*d*) (*SS*)-10.4PF_6: (*a*) (*SS*)-7: Bromination (Br_2, PPh_3) of (*SS*)-6[14] in MeCN gave (*SS*)-7 in 92% yield, $[\alpha]_D$ +25.8° (c, 2.02 in $CHCl_3$), CIMS: m/z = 446 $(M+NH_4)^+$; ^{1}HNMR ($CDCl_3$): δ = 3.40 (t, 4H), 3.70 (t, 4H), 4.45 (s, 4H), 7.00-7.20 (m, 10H). (*b*) (*SS*)-8.2PF_6: Starting from 4,4'-bipyridine and (*SS*)-7, (*SS*)-8.2PF_6 was prepared in 89% yield using a procedure identical to that employed in the preparation of 3.2PF_6. M.p. > 112°C (decomp); $[\alpha]_D$ –28.8° (c, 0.8 in MeCN); FABMS: m/z = 725 $(M-PF_6)^+$; ^{1}H NMR (CD_3CN): δ = 3.67-3.93 (m, 4H), 4.55 (s, 2H), 4.63-4.69 (m, 4H), 6.76-7.15 (m, 10H), 7.77-7.81 (m, 4H), 8.20-8.25 (m, 4H), 8.65-8.69 (m, 4H), 8.86-8.89 (m, 4H). (*c*) (*SS*)-9.4PF_6: Starting from **BBB** and (*SS*)-8.2PF_6, (*SS*)-9.4PF_6 was prepared in 23% yield using a procedure identical to that employed in the preparation of 4.4PF_6. M.p. > 258°C (decomp); $[\alpha]_D$ –34.9° (c, 0.53 in MeCN); FABMS: m/z = 1119 $(M-PF_6)^+$; ^{1}H NMR (CD_3CN): δ = 3.39 (m, 2H), 3.78 (m, 2H), 4.56 (m and s, 4H and 2H), 5.84 (bs, 4H), 6.27 (m, 4H), 6.86 (m, 4H), 6.99 (m, 2H), 7.70 (s, 4H), 7.83 (m, 4H), 8.09 (m, 4H), 8.35 (m, 4H), 8.93 (m, 4H). (*d*) (*SS*)-10.4PF_6: **BPP34C10** (62 mg, 0.12 mmol), (*SS*)-9.2PF_6 (50 mg, 0.06 mmol), and **BBB** (15.2 mg, 0.06 mmol) were dissolved in dry MeCN (6 mL) and the solution was stirred at room temperature under a nitrogen atmosphere for 14 days. It was then filtered and the filtrate was evaporated to dryness to give a highly-coloured solid which was subjected to column chromatography twice [SiO_2:MeOH/2M NH_4Cl/$MeNO_2$ (7:2:1)]. The fractions containing the product were combined, the solvents were evaporated off, and the counterions exchanged by partitioning the residue between $MeNO_2$ and saturated aqueous NH_4PF_6. The organic layer was washed well with H_2O, dried, and the solvent was removed to yield pure (*SS*)-10.4PF_6 (8.2 mg, 8%); $[\alpha]_D$ –20.4° (c, 0.049 in MeCN); FABMS: m/z = 1656 $(M-PF_6)^+$. Crystals were grown by vapour diffusion of i-Pr_2O into a Me_2CO solution of (*SS*)-10.4PF_6. Crystal data for (*SS*)-10.4PF_6:2.5Me_2CO.H_2O: orthorhombic, a = 11.784(11), b = 16.354(5), c = 49.526(52) Å, V = 9544 Å^3, space group $P2_12_12_1$, Z = 4, ρ = 1.37 g cm^{-3}, 4116 independent observed reflections with [$|F_o| > 3\sigma(|F_o|)$, $2\theta < 116°$] refined to R = 0.135, R_w = 0.129. As only *ca.* 60% of the measured data were considered to be observed, in order to maintain a reasonable ratio of observations to refined parameters, only the P, O and N atoms were refined anisotropically. The remaining non-hydrogen atoms were refined isotropically.
12. Data for (*SS*)-10.4PF_6:2.5Me_2CO.H_2O, as well as for 4.4PF_6:2$MeNO_2$.H_2O, were measured on a Nicolet R3m diffractometer using graphite monochromated $Cu_{K\alpha}$ radiation and ω-scans. The structures were solved by direct methods and refined using the SHELXTL program system. Further details of the crystal structure investigations can be obtained from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ (UK) on quoting the full journal citation.
13. In the crystals, 4^{4+} adopts an open conformation similar to that adopted by the (*SS*)-9^{4+} component of (*SS*)-10^{4+}. Although the two bipyridinium units are essentially in register with each other, they are splayed with the separations between the 'corner' CH_2 groups, in the case of the paraxylylene bridge of 5.8 Å, and of 7.4 Å in the case of the —$CH_2CH_2OCH_2CH_2OCH_2CH_2$— chain. Both the paraxylylene bridge and the two bipyridinium units display bowing with the paraxylylene C—CH_2 bonds subtending an angle of 6° and the bipyridinium N^+—CH_2 bonds subtending an angle of *ca.* 25° with concomitant twisting of the two pyridinium rings with respect to each other in both bipyridinium units of *ca.* 30°. The tetracationic cyclophanes and their associated PF_6^- counterions form continuous alternately-charged layers that are arranged in infinite stacks with a free pathway through their centres. This superstructure is very similar to that observed for cyclobis(paraquat-*p*-phenylene). The $MeNO_2$ molecules are distributed between two sites within these channels.
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(*Received in UK* 28 *March* 1994; *accepted* 6 *May* 1994)