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# Spontaneous resolution of a non-degenerate donor–acceptor [2]catenane

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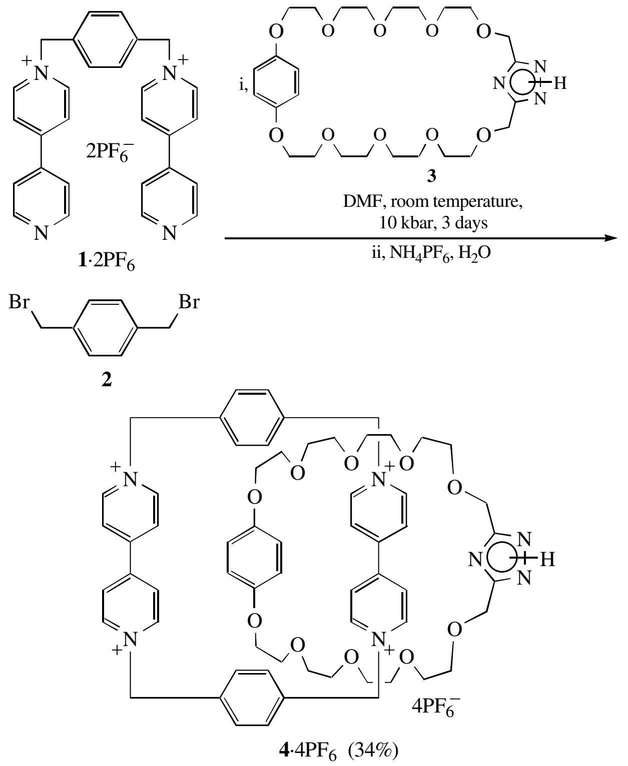
**The incorporation of a 3,5-bis(methylene)-1*H*-1,2,4-triazole unit into the macrocyclic polyether component of a donor–acceptor [2]catenane induces selectivity in the isomerization processes operating within the molecule, since it exists both in solution and in the solid state as only one of two possible translational isomers, and, upon crystallisation, undergoes spontaneous resolution under racemizing conditions.**

Catenanes and related mechanically interlocked molecules[1] are prototypes of molecular machines,[2] switches[3] and nanoscale functioning materials for the fabrication of solid-state molecular electronic devices.[4] The progressively acquired noncovalent bonds, which are responsible for the emergent molecular recognition and consequent self-assembly[5] during their template-directed syntheses,[6] 'live on' inside the molecules afterwards, and allow[7] to stimulate the relative movements of their components between two or more states. Chirality holds the key[3] when it comes to building directionality into the motions performed by molecular machines[2] and switches.[3] In this sense, exploitation of the spontaneous resolution phenomena could become an advantageous tool in order to gain directional control over the movements of large interlocked molecules. Additional interest arises from the fact that spontaneous resolution, since Pasteur's brilliant discovery,[8] has been mainly described for small and medium size molecules.[9]

Within a project aiming the study of betainic[10] [2]catenanes, we report (i) the template-directed synthesis of a [2]catenane **4**·4PF$_6$ wherein cyclobis(paraquat-*p*-phenylene) is interlocked with a polyether macrocycle containing one 3,5-bis(oxymethylene)-1*H*-1,2,4-triazole unit and one 1,4-dioxybenzene ring system, (ii) its characterisation, and (iii) the fact that the [2]catenane not only exists, both in the solution-state and in the solid-state, as strictly one of the two possible translational isomers, but that it also shows spontaneous resolution on crystallisation, leading to formation of homochiral crystals, as indicated by X-ray crystallography and circular dichroism (CD) experiments.



**Scheme 1** Template-directed synthesis of the [2]catenanes **4**·4PF$_6$.

The last step in the synthesis[11] of the [2]catenane **4**·4PF$_6$ is shown in Scheme 1. Reaction of **1**·2PF$_6$ with **2** in the presence of macrocyclic polyether **3** under high pressure (10 kbar) in DMF gave the [2]catenane **4**·4PF$_6$ in 34% yield after counterion exchange. The [2]catenane **4**·4PF$_6$ was characterised by positive-ion FAB MS, which revealed peaks for the successive loss of one, two, three and four PF$_6^-$ ions from the molecular ion. Peaks were also observed which corresponded to the loss of one, two and three counterions, respectively, from the tetracationic cyclophane of the [2]catenane, characteristic of the fragmentation of the [2]catenane by loss of one of its rings – in this case, the neutral crown ether (CE).† The $^1$H NMR spectra of **4**·4PF$_6$, recorded in CD$_3$CN solutions, indicate the presence of only one translational isomer, where the triazole units occupy the alongside position with respect to the tetracationic cyclophane, as illustrated in Scheme 1. As a proof, the hydroquinone ring protons resonate as a singlet at $\delta$ 3.56 at room temperature, indicating that the ring is residing inside the tetracationic cyclophane.

Single crystals of **4**·4PF$_6$ suitable for X-ray crystallography‡,§ were grown by vapour diffusion of Pr$^i_2$O into MeCN solution.

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† FAB MS for **4**·4PF$_6$ (*m*/*z*): 1679 [M + Na]$^+$, 1511 [M – PF$_6$]$^+$, 1366 [M – 2PF$_6$]$^+$, 1221 [M – 3PF$_6$]$^+$, 1076 [M – 4PF$_6$]$^+$, 956 [M – PF$_6$ – CE]$^+$, 811 [M – 2PF$_6$ – CE]$^+$, 666 [M – 3PF$_6$ – CE]$^+$, 683 [M – 2PF$_6$]$^{2+}$, 562 [CE + Li]$^+$.

‡ *Crystal data for* **4**·4PF$_6$·2.6MeCN·H$_2$O: [C$_{62}$H$_{73}$N$_7$O$_{10}$](PF$_6$)$_4$·2.6MeCN·H$_2$O, $M$ = 1780.9, triclinic, $P$1 (no. 1), $a$ = 12.215(1) Å, $b$ = 13.148(1) Å, $c$ = 14.137(1) Å, $\alpha$ = 109.87(1)°, $\beta$ = 103.31(1)°, $\gamma$ = 102.17(1)°, $V$ = = 1971.5(2) Å$^3$, $Z$ = 1, $d_{\text{calc}}$ = 1.500 g cm$^{-3}$, $\mu$(CuK$\alpha$) = 1.96 mm$^{-1}$, $T$ = = 193 K, orange shards; 6437 independent measured reflections, $F^2$ refinement, $R_1$ = 0.050, $wR_2$ = 0.133, 5966 independent observed reflections [$|F_o| > 4\sigma(|F_o|)$, $2\theta \le 128°$], 1136 parameters.

§ Data were collected on Siemens P4/PC diffractometers using $\omega$-scans. The structure was solved by direct methods, and it was refined based on $F^2$ using the SHELXTL program system.[15] The absolute structure of **4**·4PF$_6$ was determined by a combination of $R$-factor tests [$R_1^+$ = 0.0502, $R_1^-$ = 0521] and by use of Flack parameters [$x^+$ = 0.06(6)].

Atomic coordinates, bond lengths, bond angles and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre (CCDC). These data can be obtained free of charge *via* www.ccdc.cam.uk/conts/retrieving.html (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336 033; or deposit@ccdc.cam.ac.uk). Any request to the CCDC for data should quote the full literature citation and CCDC reference number 190346. For details, see 'Notice to Authors', *Mendeleev Commun.*, Issue 1, 2003.

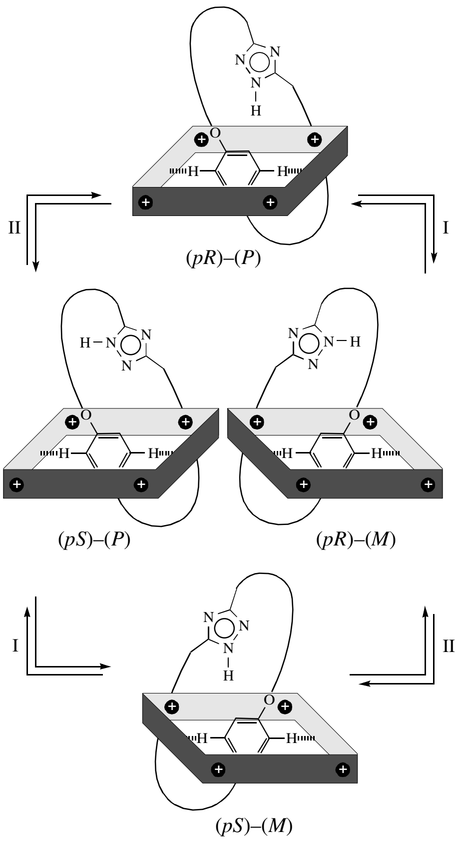

**Figure 1** Processes (I and II) for interconverting diastereoisomers and inverting enantiomers of [2]catenane $\mathbf{4}^{4+}$. Process I corresponds to a change in helical chirality while process II represents an alteration of planar chirality.

Remarkably, the monocrystal contains only one pure enantiomer, *i.e.*, spontaneous resolution occurs upon crystallisation.[9] Although this is not an uncommon phenomenon, it is, to our knowledge, the first time[12] that a non-degenerate [2]catenane has been observed to undergo spontaneous resolution. Additional features that make this case unique include (i) one of the elements of chirality arises from the relative orientation of the two macrocycles with respect to their mutual mechanical bond, (ii) the remaining chiral elements all reside exclusively in one of the two component macrocycles and (iii) inversion of one of the sources of chirality can occur by a prototropic annular tautomerism. Figure 1 shows the inversion between two pairs of enantiomers, *i.e.*, (*pR*)–(*P*) and (*pS*)–(*M*), and (*pR*)–(*M*) and (*pS*)–(*P*), *via* diastereoisomers in a mutual fashion that requires the sequential operation of two independent processes I and II.[13] The first of these processes involves rocking of the macrocyclic polyether ring with respect to the tetracationic cyclophane and the second, either rotation of the triazole ring about its C(3)–C(5) axis or a 1,2-shift of the proton on the triazole ring.

The solid-state (absolute) structure (Figure 2) of $\mathbf{4}^{4+}$ reveals that the hydroquinone ring is positioned inside the tetracationic cyclophane with the triazole ring lying alongside. The mutual arrangements of the π-electron rich hydroquinone ring are very similar to those of other catenanes of this type,[1] and so are the geometrical parameters for π–π interactions. For instance, the interplanar separation between the alongside triazole ring system and the inside bipyridinium unit is *ca.* 3.57 Å. The π–π stacking interactions are supplemented by intra-[2]catenane [C–H···O] and [C–H···π] interactions (*a*–*e* in Figure 2). There is no intra-[2]catenane [N–H···X] hydrogen bond involving the triazole ring, the ring hydrogen atom being directed toward the only ordered $\mathrm{PF}_6^-$ anion, forming an [N–H···F] hydrogen bond ([N···F], [H···F], 2.97, 2.14 Å, [N–H···F], 153°). There is, surprisingly, no formation of continuous polar stacks and the shortest inter-[2]catenane contact of any significance is from one of the methylene hydrogen atoms of the tetracationic cyclophane in one molecule to one of the *p*-xylylene spacers in the next, though the [H···π] distance is long at 3.10 Å.

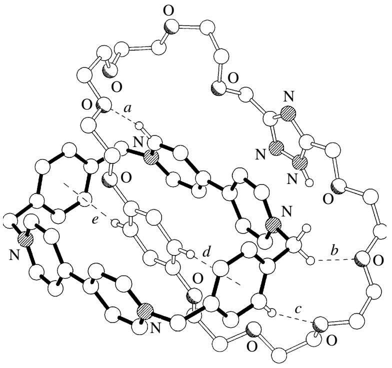

**Figure 2** A ball-and-stick representation of the solid-state structure of the (*pR*)–(*P*) isomer of $\mathbf{4}^{4+}$ showing the intra-[2]catenane hydrogen bonding interactions. The hydrogen bond geometries, [C···O], [H···O] (Å), [C–H···O] (°) are (*a*) 3.37, 2.44, 144; (*b*) 3.24, 2.44, 140; (*c*) 3.41, 2.49. 159. The CH/π interactions have [H···π] (Å), [C–H···π] (°) of (*d*) 2.70, 169; (*e*) 2.99, 158.

Single crystals (300–500 μg) of $\mathbf{4}\cdot 4\mathrm{PF}_6$ were used to prepare KBr disks,[14] and their CD spectra were recorded. Amongst 14 crystals, three exhibited a low intensity Cotton effect at *ca.* 400 nm associated with a π–π transition between the bipyridinium units and the hydroquinone ring present in the [2]catenane. The other 11 crystals were presumably twinned. The solid-state CD spectra of these enantiomorphic crystals, which exhibit maxima at 397 nm ($\Delta\varepsilon$ = +0.11 dm$^3$ mol$^{-1}$ cm$^{-1}$) and 403 nm ($\Delta\varepsilon$ = –0.18 dm$^3$ mol$^{-1}$ cm$^{-1}$), are shown in Figure 3. The solid-state CD experiments have demonstrated the presence in a single crystal of a pure single enantiomer – presumably either (*pR*)–(*P*) or (*pS*)–(*M*) – in the solid state, *i.e.*, chiral induction and spontaneous resolution occurs to give a conglomerate under freely racemizing conditions.

In light of the many solid-state structures of [2]catenanes of this kind, which do not resolve spontaneously on crystallisation, this example appears to be exceptional at this time. The reasons for the spontaneous resolution might be associated with the disturbance in the crystal of the well-established continuous polar π-donor/π-acceptor stack and could be exploited in the future as an element of control for the movements occurring within this type of catenanes.

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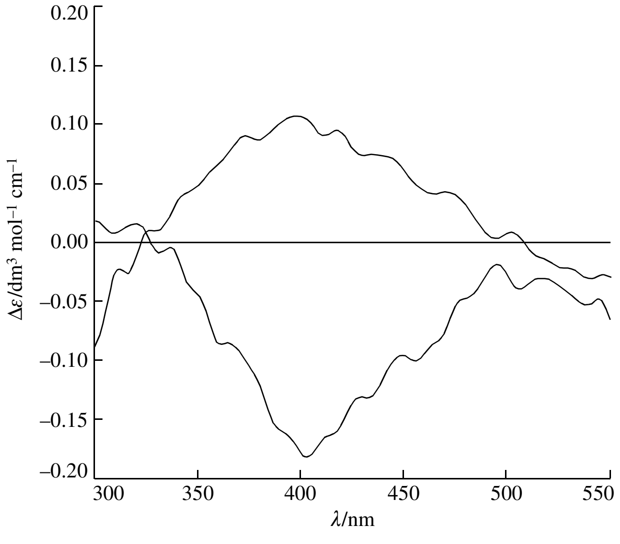

**Figure 3** Solid-state circular dichroism spectra of ‘enantiomorphic crystals’ of the [2]catenane $\mathbf{4}\cdot 4\mathrm{PF}_6$.

Institut de Ciència de Materials (CSIC, Barcelona), and Professor E. L. Eliel, University of North Carolina (Chapel Hill), for stimulating and helpful discussions.

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