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Spontaneous resolution in a family of [2]catenanes containing proton-ionisable 1*H*-1,2,4-triazole subunits

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A new donor–acceptor [2]catenane incorporating one 3,5-bis(methylene)-1*H*-1,2,4-triazole unit and one 1,5-dioxynaphthalene unit in the macrocyclic polyether component undergoes spontaneous resolution upon crystallisation, providing evidence that the inclusion of this triazole unit in the neutral component favours the phenomenon.

Catenanes and related molecular architectures have, over the past decade, been transformed from mere chemical and intellectual curiosities into key elements in the fabrication of nanoscale devices, including light- and redox-driven switches and most recently molecular logic gates.[1(a),(b)] A decisive contributory factor to these advances has been the development of templated syntheses that utilize non-covalent interactions as a major element of the self-assembly methodology,[1(c),(d)] as well as the interdisciplinary research leading to singular approaches for the construction of molecular devices.[2]

Stereochemistry can induce directionality to motion and, therefore, chirality could be regarded as a control element for the construction of molecular switches and binary optical data storage devices.[1(b)] A vast number of either configurational,[3(a)] conformational,[3(b)] or topologically[3(c),(d)] chiral interlocked systems has been described, and a big effort has been made to isolate them in an enantiomerically pure form.[4]

Incorporation of betainic subunits, *e.g.*, based on imidazolium-methylene 1,2,4-triazolate subunits, in order to build up oligopolar and oligocationic macrocylic scaffolds[5] has been one of our research interests. Recently,[6] we described the spontaneous resolution exhibited by the non-degenerate donor–acceptor [2]catenane **1**·4PF$_6$. The 3,5-bis(methylene)-1*H*-1,2,4-triazole unit incorporated into its macrocyclic polyether was considered to be responsible for the spontaneous resolution, and this might be exploited as an element of switch for the construction of potential molecular machines.

In order to investigate whether the spontaneous resolution of compound **1**·4PF$_6$ has to be considered a curiosity or a structure-related property of this type of [2]catenanes, we decided to prepare [2]catenanes incorporating 1*H*-1,2,4-triazole units in different positions, such as **2**·4PF$_6$ and **3**·4PF$_6$. Here, we report on the [2]catenane **2**·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 1,5-dioxynaphthalene ring system. The [2]catenane exists as one of the two possible translational isomers and also exhibits spontaneous resolution on crystallisation, as shown by X-ray crystallography.

Compound **2**·4PF$_6$ was self-assembled in 65% yield from the corresponding macrocyclic polyether and the immediate open chain precursors of the tetracationic cyclophane component.[7] It was characterised by positive-ion FAB MS, which revealed peaks for the successive three and four PF$_6^-$ ions from the molecular ion. Peaks were also observed, which correspond to the loss of one, two and three counterions, respectively, from the tetracationic cyclophane component, characteristic of the fragmentation of the [2]catenane by loss of one of its rings – in this case, the neutral crown ether (CE).[†]

Single crystals suitable for X-ray crystallography[‡,§] were grown by vapour diffusion of Pr$^i_2$O into an acetonitrile solution of the catenane. The crystal structure shows that it exists as only one translational isomer (Figure 1). Additionally, Figure 1 shows the absolute configuration for the crystal selected. Undoubtedly, the most remarkable feature of the solid state structure for **2**·4PF$_6$ is that the compound has spontaneously resolved on crystallisa-

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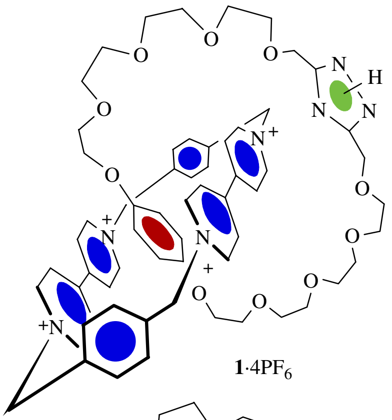
[†] FAB MS for **2**·4PF$_6$, *m*/*z*: 1271 [M – 3PF$_6$]$^+$, 1126 [M – 4PF$_6$]$^+$; 956 [M – PF$_6$-CE]$^+$, 811 [M – 2PF$_6$-CE]$^+$, 666 [M – 3PF$_6$-CE]$^+$, 708 [M – 2PF$_6$]$^{2+}$.

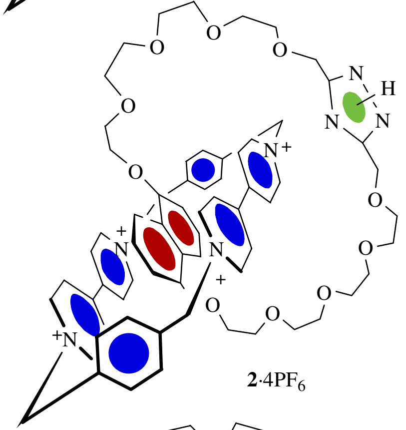
[‡] *Crystal data for* **2**·(PF$_6$)$_{3.2}$·(ClO$_4$)$_{0.8}$·3MeCN: triclinic, a = 12.302(1), b = 13.807(2), c = 14.229(2) Å, β = 102.84(1)°, V = 2003.1(4) Å^3, space group $P1$ (no. 1), Z = 1, d_{calc} = 1.486 g cm^{-3}, μ(CuKα) = 1.96 mm^{-1}, 5806 independent observed reflections with [$|F_0| > 4\sigma(|F_0|)$, θ range 3.6–64.0°] refined to R = 0.059, wR_2 = 0.160.

[§] Data were collected on a Siemens P4/PC diffractometer using ω-scans. The structure was solved by direct methods, and it was refined based on F^2 using the SHELXTL program system (version 5.1, Bruker AXS, Madison, WI, 1997). The absolute structure of **2** was determined by a combination of R-factor tests [R_1^+ = 0.0591, R_1^- = 0.0605] and by use of Flack parameters [x^+ = +0.12(6)].

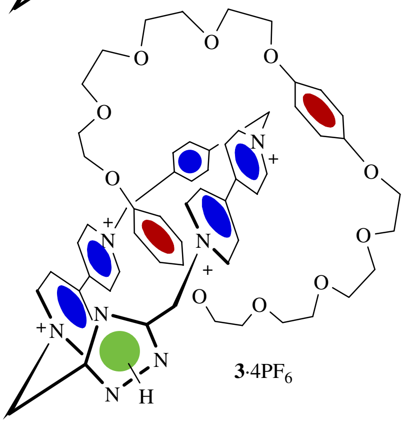
Atomic coordinates, bond lengths, bond angles and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre (CCDC). These data can be obtained free of charge *via* www.ccdc.cam.uk/conts/retrieving.html (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336 033; or deposit@ccdc.cam.ac.uk). Any request to the CCDC for data should quote the full literature citation and CCDC reference number 190347. For details, see 'Notice to Authors', *Mendeleev Commun.*, Issue 1, 2004.



1·4PF$_6$



2·4PF$_6$



3·4PF$_6$

tion, and the crystals are found to contain only a single conformational enantiomer (Figure 1).

In the structure of **2**·4PF$_6$, the anion exchange is apparently incomplete, the ‘fourth’ PF$_6$ anion being overlaid by a partial occupancy ClO$_4$ ion in a *ca.* 20:80 ratio. The π-electron rich 1,5-dioxynaphthylene ring system is positioned inside the tetracationic cyclophane, whilst the triazole ring lies only approximately alongside (Figure 1), being noticeably ‘slipped’ from the overlaying position observed in **1**·4PF$_6$. Consistent with the stronger π-stacking interaction between the 1,5-dioxynaphthylene ring system (*cf.* 1,4-dioxybenzene) and the bipyridinium units, the mean interplanar separations are reduced by more than 0.1 Å (*cf.* those seen in **1**·4PF$_6$). The ‘slipping’ of the triazole ring results in it lying above the plane of the tetracationic cyclophane with negligible overlap with either of the two pyridinium ring systems. The triazole ring and one of its adjacent CH$_2$OCH$_2$ groups are disordered, resulting in two slightly different orientations (the major occupancy conformer is depicted in Figure 1); the position of the ring hydrogen atom could not be determined. Intra-[2]catenane stabilization interactions include the usual complement of C–H···O and C–H···π hydrogen bonds, which supplement the π–π stacking (*a* to *d* in Figure 1). Surprisingly, despite the presence of three ‘ordered’ PF$_6$ anions, there are no short F···[2]catenane contacts. Again, there is no formation of extended polar stacks, nor are there any noteworthy inter-[2]catenane short contacts, though there is a methylene···*p*-xylyl approach analogous to that described for **1**·4PF$_6$ but with an even longer H···π distance of 3.19 Å.

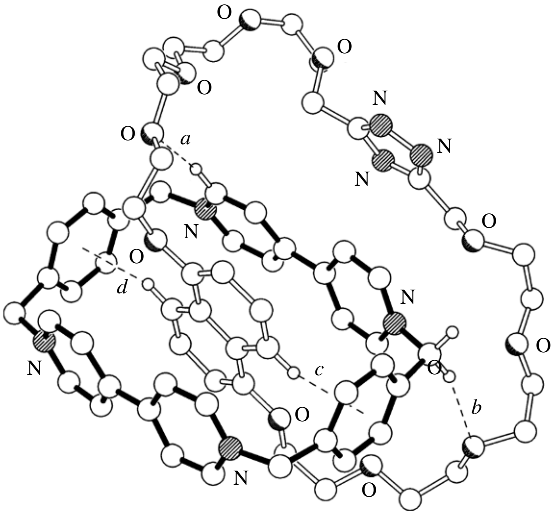


Figure 1 Molecular structure of **2**$^{4+}$ showing the intra-[2]catenane hydrogen bonding interactions. The hydrogen bonding geometries, C···O, H···O (Å), C–H···O (°) are (*a*) 3.23, 2.34, 154 and (*b*) 3.42, 2.50, 162, and the H···π interactions have H···π (Å), C–H···π (°) (*c*) 2.54, 148 and (*d*) 2.50, 150.

The basis for the chirality of [2]catenane **2**·4PF$_6$ is helical, as well as planar, and inversion between enantiomers (Figure 2) involves a co-conformational change and either a conformational change or a prototropic annular tautomerism. Figure 2 illustrates the full sequence of events related to the successive processes of interconversion between diastereoisomers that lead to the inversion of enantiomers, *i.e.*, (*pR*)–(*pR*) and (*pS*)–(*pS*), and (*pR*)–(*pS*) and (*pS*)–(*pR*). In this case, before ring rocking can occur in **2**$^{4+}$, the 1,5-dioxynaphthalene ring system has to leave the cavity of the tetracationic cyclophane, rotate around the axis of its central carbon–carbon bond and re-enter the cavity with a different relative orientation in a process which is tantamount to its having undergone rocking.

Unfortunately, a solid state circular dichroism study was not possible for the [2]catenane **2**·4PF$_6$, due to the small size of the single crystals obtained. However, a KBr disk was prepared by using several ground crystals of the compound, and the CD spectrum recorded showed no signal. This result indicates the formation of a conglomerate, *i.e.*, the existence of both enantiomers in the crystal mixture due to the spontaneous resolution phenomenon. This observation allows us to rule out the possibility of the exclusive crystallisation of one enantiomer, possible as a consequence of a rapid equilibration of the enantiomers in solution, *i.e.*, spontaneous resolution under racemising conditions.[8]

The solution state behaviour of **2**·4PF$_6$, was monitored by ^{1}H NMR spectra recorded in CD$_3$CN solutions, which indicate the presence of only one translational isomer where the triazole units occupy the alongside position with respect to the tetracationic cyclophane. This situation is evidenced by the observed δ values of 6.27, 6.01, and 2.48 for the H-2/6, H-3/7 and H-4/8 protons of the 1,5-dioxynaphthalene ring system in the spectrum of **2**·4PF$_6$ at room temperature are indicative of the position it occupies inside the tetracationic cyclophane in this [2]catenane. Thus, circumrotation of the macrocyclic polyether through the cavity of the tetracationic cyclophane is not occurring with no exchange of the 1,5-dioxynaphthalene and 3,5-bis(oxymethyl)-1*H*-1,2,4-triazole rings between the inside and alongside positions on the NMR timescale.

In contrast, catenanes incorporating 1,2,4-triazole rings in the tetracationic cyclophane component of the catenane, such as **3**·4PF$_6$, do not resolve spontaneously upon crystallisation.[7] Therefore, the structural requirements leading to the spontaneous resolution are undoubtedly linked to the position of the 1*H*-1,2,4-triazole unit within the [2]catenane, which plays a key role governing the process. When this unit is present in the

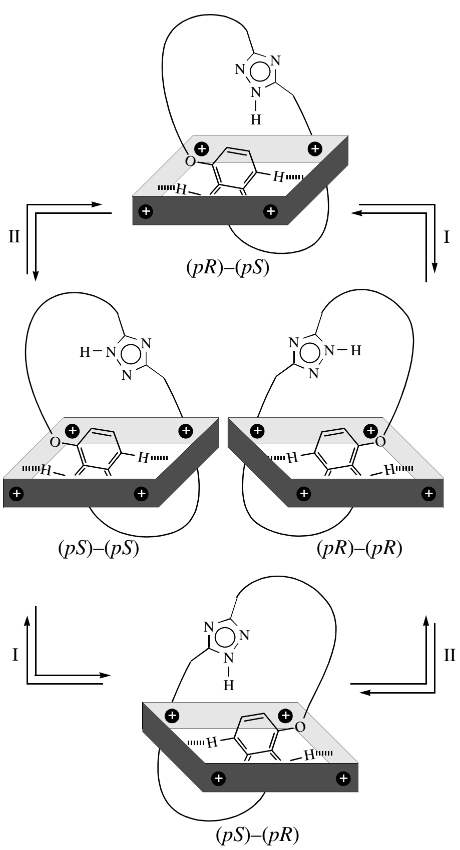


Figure 2 Processes (I and II) for interconverting diastereoisomers and inverting enantiomers in [2]catenane **2**$^{4+}$. Process I corresponds to a change in the planar chirality of the 1,5-dioxynaphthalene ring system and process II represents an alteration of the planar chirality of the 3,5-bismethylene-1*H*-1,2,4-triazole unit.

macrocyclic polyether component, the spontaneous resolution is apparently favoured.

In summary, a family of donor–acceptor [2]catenanes exhibiting spontaneous resolution emerges from the incorporation of the proton-ionisable 1,2,4-triazole unit in the macrocyclic polyether component of these types of [2]catenanes. To exploit these new properties justifies further study, and undoubtedly the potential for controllable chirality offers promising perspectives for the construction of chiroptical devices.

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References

1 (*a*) *Molecular Machines*, Special Issue, *Acc. Chem. Res.*, 2001, **34**; (*b*) *Molecular Switches*, ed. B. L. Feringa, Wiley-VCH, Weinheim, 2001; (*c*) *Molecular Catenanes, Rotaxanes and Knots*, eds. J.-P. Sauvage and C. O. Dietrich-Buchecker, Wiley-VCH, Weinheim, 1999; (*d*) *Templated Organic Synthesis*, eds. F. Diederich and P. Stang, Wiley-VCH, New York, 2000.

2 (*a*) E. W. Wong, C. P. Collier, M. Bëhloradsky, F. M. Raymo, J. F. Stoddart and J. M. Heath, *J. Am. Chem. Soc.*, 2000, **122**, 5831; (*b*) C. P. Collier, J. O. Jeppesen, Y. Luo, J. Perkins, E. W. Wong, J. R. Heath and J. F. Stoddart, *J. Am. Chem. Soc.*, 2001, **123**, 12632, and references therein.

3 (*a*) M. Asakawa, P. R. Ashton, W. Hayes, H. M. Janssen, E. W. Meijer, S. Menzer, D. Pasini, J. F. Stoddart, A. J. P. White and D. J. Williams, *J. Am. Chem. Soc.*, 1998, **120**, 920; (*b*) J.-C. Chambron, J.-P. Sauvage, K. Mislow, A. de Cian and J. Fischer, *Chem. Eur. J.*, 2001, **7**, 4086; (*c*) F. Vögtle, T. Dünnwald and T. Schmidt, *Acc. Chem. Res.*, 1996, **29**, 451; (*d*) J.-C. Chambron, D. K. Mitchell and J.-P. Sauvage, *J. Am. Chem. Soc.*, 1992, **114**, 4625; (*e*) P. R. Ashton, S. E. Boyd, S. Menzer, D. Pasini, F. M. Raymo, N. Spencer, J. F. Stoddart, A. J. P. White, D. J. Williams and P. G. Wyatt, *Chem. Eur. J.*, 1998, **4**, 299.

4 (*a*) C. Reuter, A. Mohry, A. Sobanski and F. Vögtle, *Chem. Eur. J.*, 2000, **6**, 1674; (*b*) C. Reuter, R. Schmieder and F. Vögtle, *Pure Appl. Chem.*, 2000, **72**, 2233.

5 E. Alcalde, M. Alemany, N. Mesquida, L. Pérez-García, S. Ramos and M. L. Rodríguez, *Chem. Eur. J.*, 2002, **8**, 474, and references therein.

6 E. Alcalde, L. Pérez-García, S. Ramos, J. F. Stoddart, S. Vignon, A. J. P. White and D. J. Williams, *Mendeleev Commun.*, 2003, 100.

7 S. Ramos, *PhD Thesis*, Faculty of Pharmacy, University of Barcelona, 2002.

8 L. Pérez-García and D. B. Amabilino, *Chem. Soc. Rev.*, 2002, 342, and references therein.

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