## THE TEMPLATE-DIRECTED SYNTHESIS OF A [2]ROTAXANE

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Summary: X-Ray crystallography, FABMS, and <sup>1</sup>H and <sup>13</sup>C NMR spectroscopy have all been employed in the characterisation of a self-assembled [2]rotaxane composed of (i) a polyether chain intercepted by a centrally-located  $\pi$ -electron rich hydroquinol ring and terminated by adamantoyl groups and (ii) a tetracationic cyclophane constructed by two  $\pi$ -electron deficient bipyridinium units linked by paraphenylenedimethyl residues.

Following on from the highly efficient template-directed synthesis<sup>1</sup> of a [2]catenane constructed of (i) a bisparaphenylene-34-crown-10 macrocycle<sup>2</sup> and (ii) a tetracationic cyclophane<sup>3</sup> composed of two bipyridinium units linked by two paraphenylenedimethyl residues, we have synthesised<sup>4</sup> the [2]rotaxane **1.4**PF<sub>6</sub> in a similar manner.<sup>5-7</sup> Dynamic <sup>1</sup>H NMR spectroscopy revealed<sup>4</sup> that this [2]rotaxane (**Figure 1**) behaves like a molecular shuttle: at room temperature, the tetracationic 'bead' moves to and fro like a shuttle approximately 500 times a second between two identical 'stations' in the shape of hydroquinol rings incorporated symmetrically into a polyether 'thread' terminated at both ends by bulky tri-isopropyl silyl protecting groups which act as 'stoppers'. Here, we report the synthesis (**Scheme 1**), by a clipping procedure,<sup>5</sup> of a [2]rotaxane **5**<sup>4+</sup> in which the polyether 'thread' contains only *one* hydroquinol ring and is terminated by adamantoyl groups.<sup>8</sup> We describe how this new [2]rotaxane has been characterised by FABMS, <sup>1</sup>H and <sup>13</sup>C NMR spectroscopies, and X-ray crystallography.

Reaction (Scheme 1) of equimolar amounts of 2.2PF6 and 3 in MeCN at room temperature (RT) for 7 days



Figure 1. The [2] rotaxane  $1.4PF_6$  behaving as a molecular shuttle. The shuttling process is a degenerate one wherein the hydroquinol rings labelled A and B occupy alternately alongside and inside positions with respect to the tetracationic cyclophane.



in the presence of an excess of 4 (1.5 mol equiv) and AgPF<sub>6</sub> (2.2 mol equiv) gave<sup>9</sup> 5.4PF<sub>6</sub> as a deep reddishorange solid in 10% yield. Vapour diffusion of pentane into an acetone solution of 5.4PF<sub>6</sub> afforded single crystals suitable for X-ray crystallography.<sup>10</sup> The solid state structure (Figure 2) of 5<sup>4+</sup> shows that the 'thread' is inserted through the centre of the tetracationic 'bead' in a centrosymmetric fashion such that the  $\pi$ -electron rich hydroquinol ring is totally encircled by the two  $\pi$ -electron deficient bipyridinium units which enter into  $\pi/\pi$ -stacking interactions<sup>11</sup> whilst the two paraphenylenedimethyl rings are involved in stabilising electrostatic edge-to-face (centroid--centroid distance, 5.10 Å) interactions.<sup>12</sup> The mean plane separations between the bipyridinium units and the encircled hydroquinol ring are ca. 3.5 Å and the angle of tilt between the O···O vector of the hydroquinol ring and the N···N axis of the bipyridinium units is 44°. The tetracationic cyclophane displays a characteristic barrel shape with the C-CH<sub>2</sub> bonds emanating from the paraphenylene units subtending an angle of 11° and the N+--CH2 bonds associated with the bipyridinium units subtending an angle of 24° in relation to their respective ring planes. In addition to the bowing of the bipyridinium units, there is significant twisting (23°) of the bipyridinium rings with respect to each other. Like the tri-isopropyl silyl 'stoppers' in the molecular shuttle  $1^{4+}$ , the adamantoyl units in  $5^{4+}$  are sufficiently bulky to prevent the tetracationic 'bead' from slipping off the ends of the polyether 'thread', rendering 54+ a genuine [2]rotaxane. However, in the positive-ion FABMS<sup>13</sup> of 5.4PF<sub>6</sub>, not only do we witness loss of one, two, and three  $PF_6^-$  counterions (m/z = 1653, 1508, 1363), but we also observe the peaks at m/z = 955, 810, 665 for the analogous counterion losses from the tetrakishexafluorophosphate of the free tetracationic cyclophane as a result of fragmentation of one of the adamantoyl groups from the polyether 'thread' 4 leading to the 'flying apart' of the molecular components of the [2]rotaxane. In solution, the molecular components of  $5^{4+}$  have a gross structural relationship to each other which is similar to that (Figure 2) present in the solid state. Thus, the <sup>1</sup>H (400 MHz) and <sup>13</sup>C (100 MHz) NMR spectra recorded in CD<sub>3</sub>CN reveal substantial shielding of the hydroquinol ring protons ( $\Delta \delta = -3.2$  ppm) and carbon atoms ( $\Delta \delta = -2.0$  and -1.6 ppm) in 5.4PF<sub>6</sub>. The encirclement of the hydroquinol ring in the polyether 'thread' by the tetracationic 'bead' is also implied by the deep reddish-orange colour of the solutions indicating that charge transfer interactions are occurring between the  $\pi$ -electron rich hydroquinol ring and the  $\pi$ -electron deficient bipyridinium units in 5<sup>4+</sup>.

The template-directed synthesis of  $5^{4+}$ indicates that the molecular components of a simple [2]rotaxane can be brought together and made to order in a molecular self-assembly process<sup>14</sup> which depends upon the cooperative action of numerous noncovalent bonding interactions.

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## **References and Footnotes**

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- Preparation of 4: Bisalkylation (K<sub>2</sub>CO<sub>3</sub>/DMF/80°C/3 days) of 1,4-dihydroxybenzene with 2-[2-(2-choloroethoxy)ethoxyethanol| gave (SiO<sub>2</sub>:CH<sub>2</sub>Cl<sub>2</sub>/Me<sub>3</sub>COMe/MeOH, 76:20:4) a crystalline diol (69%) which was esterified with 1-adamantanecarbonyl chloride in dry pyridine at 70°C overnight to afford (SiO<sub>2</sub>: Me<sub>3</sub>COMe) a low melting solid 4 (59%) [FABMS: m/z = 721 ([M+Na]<sup>+</sup>), 698 (M<sup>+</sup>); <sup>1</sup>H-NMR (CDCl<sub>3</sub>): δ = 1.70-1.83 (m, 12H), 1.90-1.98 (m, 12H), 1.98-2.10 (m, 6H), 3.64-3.82 (m, 16H), 4.10 (t, 4H), 4.24 (t, 4H), 6.85 (s, 4H); <sup>13</sup>C-NMR (CDCl<sub>3</sub>): δ 27.8, 36.4, 38.7, 40.6, 63.2, 68.0, 69.2, 69.8, 70.6, 70.7, **115.5**, **153.0**, 177.5. The δ values for the hydroquinol ring protons and carbon atoms are featured in **bold-face**.
- Preparation of 5.4PF<sub>6</sub>: 3 (59 mg, 0.2 mmol), 2.2PF<sub>6</sub> (152 mg, 0.2 mmol), 4 (214 mg, 0.3 mmol), and AgPF<sub>6</sub> (120 mg, 0.4 mmol) were dissolved in dry MeCN (25 mL) and the solution was stirred at room temperature in the dark for 7 days. The solvent was removed *in vacuo* to afford a reddish-orange solid which was subjected to chromatography [SiO<sub>2</sub>:2M NH<sub>4</sub>Cl/MeOH (4:3) saturated with MeNO<sub>2</sub>]. A saturated aqueous NH<sub>4</sub>PF<sub>6</sub> solution was added to the fraction of the eluant containing the [2]rotaxane 5<sup>4+</sup>. The solution was extracted with MeNO<sub>2</sub>. Evaporation of the solvent gave a reddish-orange solid, which was crystallised by diffusing pentane vapour into an acetone solution, to give, after drying, 5.4PF<sub>6</sub> (35 mg, 10%), m.p. > 285°C [FABMS: *m*/z 1653 ([*M*-PF<sub>6</sub>]<sup>+</sup>), 1508 ([*M*-2PF<sub>6</sub>]<sup>+</sup>), 1363 ([*M*-3PF<sub>6</sub>]<sup>+</sup>); <sup>1</sup>H-NMR (CD<sub>3</sub>CN): δ = 1.56-1.72 (m, 12H), 1.76-1.79 (m, 12H), 1.86-1.92 (m, 6H), 3.59 (s, 4H), 3.62-3.66 (m, 4H), 3.78-3.82 (m, 4H), 3.87-3.92 (m, 8H), 3.92-3.94 (m, 4H), 4.17-4.21 (m, 4H), 5.69 (s, 8H), 7.80 (s, 8H), 7.83 (d, 8H), 8.93 (d, 8H); <sup>13</sup>C-NMR (CD<sub>3</sub>CN): 28.9, 37.0, 39.6, 41.5, 63.9, 65.8, 67.7, 70.2, 70.8, 71.7, 71.9, **113.9**, 127.1, 131.9, 137.6, 145.7, 147.7, **151.0**, 178.1. The δ values for the hydroquinol ring protons and carbon atoms are featured in **bold-face**.
- 10. Crystal data for 5.4PF<sub>6</sub>.4Me<sub>2</sub>CO: triclinic, a = 12.077(3), b = 14.009(4), c = 17.588(6) Å,  $\alpha = 82.45(3)$ ,  $\beta = 78.48(2)$ ,  $\gamma = 64.86(2)^\circ$ , V = 2636 Å<sup>3</sup>, space group P1, Z = 1 (the molecule is disposed about a centre of symmetry,  $\rho = 1.28$  g cm<sup>-3</sup>,  $\mu$ (Cu-K $\alpha$ ) = 14 cm<sup>-1</sup>, 6610 independent measured reflections ( $\theta \le 55^\circ$ ) of which 3581 were considered to be observed [ $|F_0| \ge 3\sigma(|F_0|)$ ]. Data were measured on a Nicolet R3m diffractometer with graphite-monochromated Cu-K $\alpha$  radiation using  $\omega$ -scans. The structure was solved by direct methods and refined anisotropically. Because of the high thermal motion of the adamantoyl unit and its associated polyether 'thread', this portion of the molecule was optimised and refined subject to C—C and C—O distance constraints. This poor resolution, coupled with the presence of partial occupancy solvent molecules and characteristically disordered PF<sub>6</sub><sup>-</sup> ions, resulted in the high final values of R = 0.174,  $R_w = 0.169$ . Computations were carried out on an Eclipse S140 computer using the SHELXTL program system. Further details of the crystal structure can be obtained from the Cambridge Crystallographic Data Centre, University Chemical Laboratory, Lensfield Road, Cambridge CB2 1EW, England.
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