A Molecular Shuttle

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When noncovalent bonding interactions are a stabilizing feature between the components of a [2]catenane[1,2] and [2]rotaxanes,[2] then they retain within their interlocked molecular structures[2-4] the relative order that templates initially their syntheses. The degenerate dynamic properties[1,2] of such a [2]catenane encouraged us to design a [2]rotaxane **5** (Scheme I) that would function (Scheme II) as a molecular shuttle, i.e., a molecular assembly in which a tetracationic "bead" moves back and forth like a shuttle[5] between two identical "stations" in the form of hydroquinol units grafted symmetrically into a polyether "thread" terminated at the ends by large triisopropylsilyl groups that act as "stoppers". Here, we describe the noncovalently templated synthesis (Scheme I) of **5** and demonstrate, from the temperature dependence of its NMR spectra, that it does indeed behave (Scheme II) like a molecular shuttle.

The diphenol **2**[6] was bisalkylated (Scheme I) with **1** to afford (54%) a diol,[7] which was converted (78%) into its bis(triisopropylsilyl) ether, i.e., the polyether "thread". Reaction of equimolar amounts of **4**·$2PF_6$ with **3** in MeCN at room temperature for 7 days in the presence of an excess (3.0 molar equiv) of the polyether "thread" and $AgPF_6$ (2.5 molar equiv)[8] gave **5**·$4PF_6$ as a deep-orange colored product[9] in the relatively high yield of 32%, presumably as a result of templating action[10] during the cyclization of the tricationic precursor to afford the tetracationic "bead".[11]

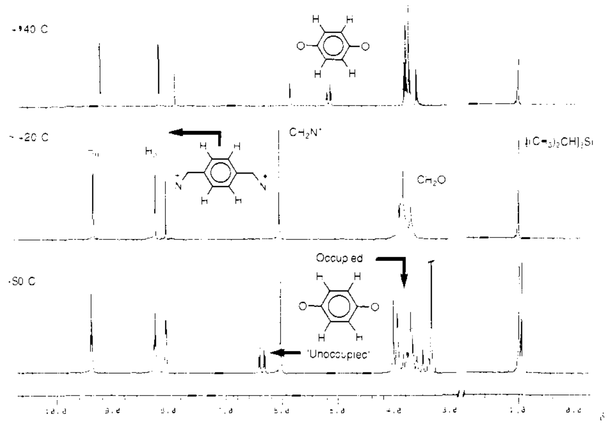

Figure 1. The ^1H NMR spectra of **5**·$4PF_6$ recorded at +140 °C in CD_3SOCD_3 and at ca. +20 °C and −50 °C in CD_3COCD_3.

The ^1H NMR spectrum (400 MHz) of **5**·$4PF_6$ exhibits temperature dependence (Figure 1). At ambient temperature in CD_3COCD_3 solution, the signals (δ 3.65–3.96) for the OCH_2 protons are broad while those for the hydroquinol ring protons are merged in with the base line between δ 3.5 and 6.5. When the same sample is warmed up to +140 °C in CD_3SOCD_3 solution, an AA′BB′ system centered on δ 5.16 can be identified for these protons. When the CD_3COCD_3 solution is cooled down to −50 °C, an AA′BB′ system centered on δ 6.38 can be identified for the protons on the "unoccupied" hydroquinol ring (red in Scheme II): the protons on the "occupied" hydroquinol ring (black) were located at ca. δ 3.8 within the envelope of OCH_2 multiplets by carrying out a saturation transfer experiment[12] under conditions of slow site exchange. In addition, separation of signals is observed at low temperatures for the triisopropyl groups on the silyl "stoppers" at the ends of the polyether "thread" and on the tetracationic "bead" for (a) the α and β protons on the bipyridinium rings and for (b) the protons on the *p*-phenylene rings. The coalescences[13] of the signals associated with these *different* ^1H NMR probes in *both* components *all* afford[14] $\Delta G_c^{\ddagger}$ values of ca.

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[1] Ashton, P. R.; Goodnow, T. T.; Kaifer, A. E.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Vicent, C.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 1394–1399.

[2] Anelli, P. L.; Ashton, P. R.; Ballardini, R.; Balzani, V.; Delgado, M.; Gandolfi, M. T.; Goodnow, T. T.; Kaifer, A. E.; Philp, D.; Pietraszkiewicz, M.; Prodi, L.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Vicent, C.; Williams, D. J. *J. Am. Chem. Soc.*, in press and references therein.

[3] The early research in this field is summarized in the following: Schill, G. *Catenanes, Rotaxanes and Knots*; Academic Press: New York, 1971. For a discussion of more recent results, see: Dietrich-Buchecker, C. O.; Sauvage, J.-P. *Chem. Rev.* **1987**, *87*, 795–810.

[4] For examples of [2]rotaxanes in the literature, see: (a) Schill, G.; Zollenkopf, H. *Justus Liebigs Ann. Chem.* **1969**, *721*, 53–74. (b) Schill, G.; Henschel, R. *Justus Liebigs Ann. Chem.* **1970**, *731*, 113–119. (c) Schill, G.; Neubauer, H. *Justus Liebigs Ann. Chem.* **1971**, *750*, 76–90. (d) Schill, G.; Zürcher, C.; Vetter, W. *Chem. Ber.* **1973**, *106*, 228–235. (e) Schill, G.; Beckmann, W.; Schweichert, N.; Fritz, H. *Chem. Ber.* **1986**, *119*, 2647–2655. (f) Harrison, I. T.; Harrison, S. *J. Am. Chem. Soc.* **1967**, *89*, 5723–5724. (g) Harrison, I. T. *J. Chem. Soc., Chem. Commun.* **1972**, 231–232. (h) Harrison, I. T. *J. Chem. Soc., Perkin Trans. 1* **1974**, 301–304. (i) Ogino, H. *J. Am. Chem. Soc.* **1981**, *103*, 1303–1304. (j) Ogina, H.; Ohata, K. *Inorg. Chem.* **1984**, *23*, 3312–3316. (k) Yamanari, K.; Shimura, Y. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 2283–2289. (l) Rao, T. V. S.; Lawrence, D. S. *J. Am. Chem. Soc.* **1990**, *112*, 3614–3615.

[5] A shuttle, which is "any of various types of slender pointed wooden devices used in weaving for passing or shooting the thread of the woof between the threads of the warp from one side of the cloth to the other", also describes "a going back and forth over a specified route or path at regular intervals" applied to "such a plying by any of various vehicles (as planes, automobiles, trains, ships)". See: *Webster's Third New International Dictionary*; Merriam: Springfield, 1976.

[6] This compound can be prepared in 68% yield from 4-(benzyloxy)phenol and tetraethylene glycol bistosylate. See: Allwood, B. L.; Spencer, N.; Shahriari-Zavareh, H.; Stoddart, J. F.; Williams, D. J. *J. Chem. Soc., Chem. Commun.* **1987**, 1061–1064.

[7] All new compounds gave expected ^1H NMR and mass spectra and C, H, N analyses within 0.4% of theory.

[8] In the absence of $AgPF_6$, yields of the [2]rotaxane are lower because of the precipitation of **4** and/or the intermediate trication as their Br^- and/or Br^-/PF_6^- salts.

[9] Purification and isolation of **5** as its tetrakis(hexafluorophosphate), mp > 260 °C dec, was accomplished by column chromatography [SiO_2/MeOH–2 N aqueous NH_4Cl-$MeNO_2$ (7:2:1)] followed by anion exchange with aqueous NH_4PF_6. Positive-ion FABMS revealed two peaks at *m/z* 1910 and 1765 corresponding to the loss of one and two PF_6^- counterions, respectively, from **5**·$4PF_6$. We thank Mr. Peter R. Ashton for recording this FABMS.

[10] The noncovalent bonding includes (see ref 2) electrostatic pole–dipole attractions between the dicationic bipyridinium units and the "solvating" polyether oxygen atoms, as well as stabilizing dispersive forces including (i) π/π-stacking and charge-transfer interactions (cf: Hunter, C. A.; Saunders, J. K. M. *J. Am. Chem. Soc.* **1990**, *112*, 5525–5534) between the π-electron-rich hydroquinol rings and the π-electron-deficient bipyridinium units and (ii) electrostatic "T-type" edge-to-face interactions (cf.: Jorgensen, W. L.; Severance, D. L. *J. Am. Chem. Soc.* **1990**, *112*, 4768–4774) involving the hydroquinol rings and the *p*-phenylene units in the "bead".

[11] For a discussion of the preparation and complexing properties of this cyclophane, see: (a) Odell, B.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 1547–1550. (b) Ashton, P. R.; Odell, B.; Reddington, M. V.; Slawin, A. M. Z.; Stoddart, J. F.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 1550–1553.

[12] Irradiation at −25 °C of the AA′BB′ system centered on δ 6.45 resulted in enhancement of signal intensity at δ 3.80.

[13] Values for k_c were obtained (Sutherland, I. O. *Annu. Rep. NMR Spectrosc.* **1971**, *4*, 71–235) by using the approximate expression $k_c = \pi(\Delta\nu)/(2)^{1/2}$, and the Eyring equation was used to calculate the $\Delta G_c^{\ddagger}$ values at T_c. We recognize that many approximations are involved in this semiquantitative treatment, and so the $\Delta G_c^{\ddagger}$ values should be viewed as having at least 10% error margins.

[14] Free energy barriers to the shuttling process have been calculated from the temperature dependences (Figure 1) of (a) the α and β protons on the bipyridinium rings ($\Delta\nu$ = 7.0 Hz, k_c = 16 s^{-1}, T_c = −20 °C, $\Delta G_c^{\ddagger}$ = 13.3 kcal mol^{-1}); (b) the protons on the *p*-phenylene rings ($\Delta\nu$ = 7.6 Hz, k_c = 17 s^{-1}, T_c = −36 °C, $\Delta G_c^{\ddagger}$ = 12.4 kcal mol^{-1}); and (c) the protons on the (black and red) hydroquinol rings [$\Delta\nu$ = 1060 Hz (measured at −25 °C), k_c = 2360 s^{-1}, T_c = +34 °C, $\Delta G_c^{\ddagger}$ = 13.2 kcal mol^{-1}].

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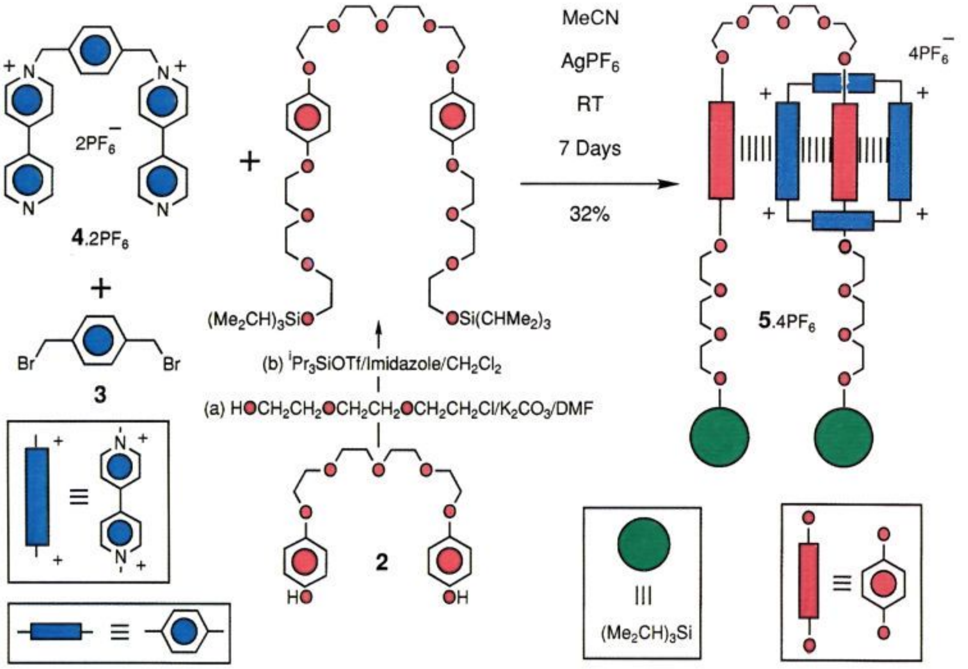
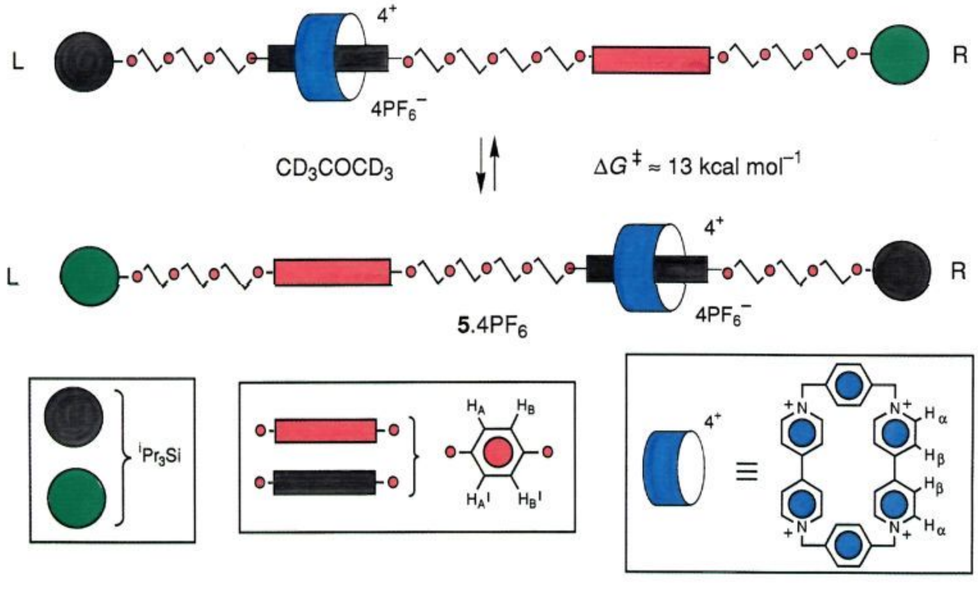
Scheme I. The Self-Assembly of a Molecular Shuttle[a]



[a] In the structural formulas and cartoons, the tetracationic "bead" and its precursors are blue, the polyether "thread" and its precursors are red, and the triisopropylsilyl "stoppers" are green.

Scheme II. A Molecular Shuttle in Action[a]



[a] In the cartoons, the tetracationic "bead" is blue, the polyether "thread", including the "unoccupied" hydroquinol ring, is red, the "occupied" hydroquinol ring is black, as is the adjacent silyl "stopper", and the other distant silyl "stopper" is green. In the degenerate shuttling process, the red and black hydroquinol rings undergo exchange as a result of the traveling back and forth of the blue tetracationic "bead", and so do the green and black silyl "stoppers".

13 kcal mol^{-1} for, we believe, a *single* process (Scheme II) of shuttling back and forth of the tetracationic "bead" between the two hydroquinol "stations" on the polyether "thread".[15] The site exchange process is a degenerate one wherein the tetracationic "bead", which occupies the black portions of the polyether "thread", alternates equally between left (L) and right (R) sides.

The opportunity now exists to desymmetrize the molecular shuttle by inserting nonidentical "stations" along the polyether "thread" in such a manner that these different "stations" can be addressed selectively by chemical, electrochemical, or photochemical means and so provide a mechanism to drive the "bead" to and fro between "stations" along the "thread". Insofar as it becomes possible to control the movement of one molecular

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[15] $^{13}C\{^1H\}$ NMR spectra of **5**·4PF$_6$ also exhibited temperature-dependent behavior expected for a shuttle process. In particular, the signals for the hydroquinol ring carbons are not evident in the spectrum recorded in CD_3COCD_3 at room temperature. However, at +75 °C in CD_3CN, shuttling is "fast" and they resonate at δ 153.1, 152.8 (C), and 115.3 (CH), whereas at −40 °C in CD_3COCD_3, shuttling is "slow" and signals are observed at δ 153.0, 152.7, and 150.6 (C) and at 115.3, 115.2, 113.4, and 113.3 (CH).

component with respect to the other in a [2]rotaxane, the technology for building "molecular machines" will emerge.

The molecular shuttle described in this communication is the prototype for the construction of more intricate molecular assemblies[2,16] where the components will be designed to receive, store, transfer, and transmit information in a highly controllable manner, following their spontaneous self-assembly[17,18] at the supramolecular[19] level. Increasingly, we can look forward to a "bottom-up" approach to nanotechnology[20] which is targeted toward the development of molecular-scale information processing systems.

Acknowledgment. This research was supported by the Agriculture and Food, and Science and Engineering, Research Councils in the United Kingdom and by Consiglio Nazionale delle Ricerche in Italy.

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(16) For a recent communication on the ordered threading of molecular components, see: Anelli, P. L.; Ashton, P. R.; Spencer, N.; Slawin, A. M. Z.; Stoddart, J. F.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.*, in press.

(17) For an outstandingly good review of self-assembly in synthetic routes to molecular devices, see: Lindsey, J. S. *New J. Chem.* **1991**, *15*, 153–180.

(18) For a review of self-assembly in organic synthesis, see: Philp, D.; Stoddart, J. F. *Synlett*, in press.

(19) (a) Lehn, J.-M. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 89–112. (b) Lehn, J.-M. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 1304–1319.

(20) *Artificial Life*; Langton, C. G., Eds.; Addison-Wesley: Redwood City, CA, 1989.

Additions and Corrections

Asymmetric Synthesis Using Diisopropyl Tartrate Modified (*E*)- and (*Z*)-Crotylboronates: Preparation of the Chiral Crotylboronates and Reactions with Achiral Aldehydes [*J. Am. Chem. Soc.* **1990**, *112*, 6339–6348]. William R. Roush,* Kaori Ando, Daniel B. Powers, Alan D. Palkowitz, and Ronald L. Halterman

Pages 6344 and 6345: The ^{1}H NMR data reported for (*R*,*R*)-diisopropyl tartrate (*E*)-crotylboronate (**2**) and (*R*,*R*)-diisopropyl tartrate (*Z*)-crotylboronate (**3**) were measured in C_6D_6, and not in $CDCl_3$ as indicated in the tabulated spectroscopic data. ^{1}H NMR data for these reagents measured in $CDCl_3$ are as follows: **2** (500 MHz, $CDCl_3$) δ 5.42–5.53 (m, 2 H), 5.11 (septet, $J = 6.5$ Hz, 2 H), 4.77 (s, 2 H), 1.83 (br d, $J = 5$ Hz, 2 H), 1.64 (br d, $J = 5$ Hz, 3 H), 1.28 (d, $J = 6.3$ Hz, 12 H); **3** (500 MHz, $CDCl_3$) δ 5.47–5.58 (m, 2 H), 5.11 (quintet, $J = 6.5$ Hz, 2 H), 4.76 (s, 2 H), 1.83–1.92 (m, 2 H), 1.61 (d, $J = 5$ Hz, 3 H), 1.28 (d, $J = 6.3$ Hz, 12 H).

Computer Software Reviews

The MSDS Solution (TMS) and SCS Access, Version 1.05. Logical Technology, Inc.: 5113 North Executive Drive, Peoria, Illinois 61614. List Prices: MSDS Solution $995.00; SCS Access $470.00; both $1365.00. The MSDS yearly maintenance is $205.00, while the SCS Access yearly subscription is $495.00. A network version is also available for an additional $850.00.

These software packages require minimally an XT (LTI recommends an AT) class IBM PC (or 100% compatible) with 640K RAM and a 20M hard disc operating with DOS 2.0 or higher. The MSDS Solution is a menu-driven outline program that allows one to enter information from a manufacturer's material safety data sheet (MSDS) into an organized format for easy filing and rapid information retrieval. OSHA's Hazard Communication Standard established the sensible guideline that all workers must have access to the safety information encapsulated in the MSDSs. Since the "worker's right-to-know" is geared more toward the industrial workplace, this software package is likely to have more application in industrial and government labs than in academia. (However, with OSHA's "Occupational Exposure to Hazardous Chemicals in Laboratories" there is currently a need in every laboratory.) The MSDS Solution allows these data to be quickly retrieved by a variety of means, including formula, product name, manufacturer, or MSDS number. Each MSDS is given a status assignment as either pending, current or non-current, or per the chemical's status in the inventory. There is a user hierarchy, allowing progressively more access and editorial power to higher ranking users. A "General User" may read current and non-current MSDS's and may utilize SCS Access to compile reports from the database. "MSDS Entry Personnel" may load and edit MSDS's and the "Coordinator" may alter the status of MSDS's, assemble user lists, and import/export MSDS's.

The format of the MSDS has fields for specific information, including manufacturer's product information, physical and chemical properties, fire and explosion data, and component information, and space is set aside for comments.

Installation of the software is simple. The demo version of the program took 7 min to load on an IBM PS 2. The complete version took a little longer. (LTI reports that in the newest version they have the loading time to 2–5 min, depending on hardware.) Initially, we had some minor difficulties in getting the loaded software to run. A phone call to Logical Technology, Inc. resulted in helpful coaching.

The failure of the loaded software to run was a result of insufficient working memory due to memory resident programs. This intolerance of other resident programs is a potential downfall of this software (albeit a very small one). Given the size of many companies' chemical inventories and the number of MSDS's that would be stored in this type of data base, dedication of a PC may be recommended anyway and at any rate is a small price to pay for this organization, speed, and convenience. The smaller companies, or those with relatively small chemical inventories, who may wish to use their PC's in multiple capacities, will need to turn off any memory resident programs to run this system.

A time-saving option would be the ability to down load commercial (e.g. Aldrich) MSDS files into this data base. However, apparently electronic MSDS's have not been standardized industry wide and it was the opinion of the helpful soul at Logical Technology, Inc. that such importing would not be possible without additional programming. So,