A Simple Construction of a Rotaxane and Pseudorotaxane: Syntheses and X-Ray Crystal Structures of Cucurbituril Threaded on Substituted Spermine

You-Moon Jeon, Dongmok Whang, Jaheon Kim, and Kimoon Kim*
Department of Chemistry and Center for Biofunctional Molecules, Pohang University of Science and Technology, San 31 Hyojadong, Pohang, 790-784, South Korea

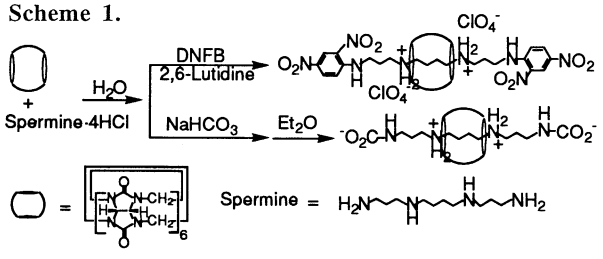
(Received February 28, 1996)

A simple, one-step, high-yield synthesis of a rotaxane and pseudorotaxane based on cucurbituril and spermine is presented. Various spectroscopic techniques and X-ray diffraction methods were used to characterize the supramolecular species.

Rotaxanes are supramolecular species in which a cyclic molecular 'bead' is threaded by a linear chain having bulky end groups (stoppers), which prevent dethreading of the 'bead'.[1] Elegant studies on the synthesis of rotaxanes by Stoddart and coworkers demonstrated how to construct such complex supramolecular species by self-assembly process.[2,3] Cyclodextrins have been used as 'beads' in the synthesis of rotaxanes in recent years.[4,5] None of the rotaxanes based on cyclodextrins, however, has been characterized by X-ray diffraction methods presumably due to difficulty in obtaining X-ray quality crystals. Similar to cyclodextrins, cucurbituril **1** has a rigid structure with a hollow core of ~5.5 Å diameter, which is accessible from the exterior by two carbonyl-fringed portals.[6] As a cavitand it forms host-guest complexes with aliphatic and aromatic mono- and diammonium ions.[7] Its easy synthesis, rigid structure and capability of holding guest molecules make cucurbituril a useful candidate for a 'bead' in rotaxane synthesis; nevertheless, no rotaxane based on cucurbituril has been reported yet. Taking advantage of its high affinity for alkyl diammonium ions we were able to synthesize a rotaxane in one step in a high yield. Thanks to the power of a new CCD-based X-ray diffractometer we were also able to characterize the rotaxane by X-ray crystallography. Here we report the syntheses and X-ray structures of a rotaxane and pseudorotaxane based on cucurbituril and spermine.

The construction of the rotaxane **3** was achieved in one step in a high yield by threading **1** by spermine **2** and then attaching dinitrophenyl groups to the both ends of the spermine molecule to prevent dethreading (Scheme 1).[8]

Scheme 1.



The rotaxane **3** was characterized by NMR, IR and mass spectroscopy, and elemental analysis.[9] ^{1}H NMR spectroscopy was particularly useful in characterization of **3**. Each peak of the NMR spectrum of **3** was assigned unequivocally by coupling connectivity in 2D-COSY spectrum. The proton signals of the internal methylene units of the spermine chain, which are placed inside the cucurbituril cavity in **3**, are shifted upfield upon formation of the rotaxane due to the strong shielding effect of cucurbituril.

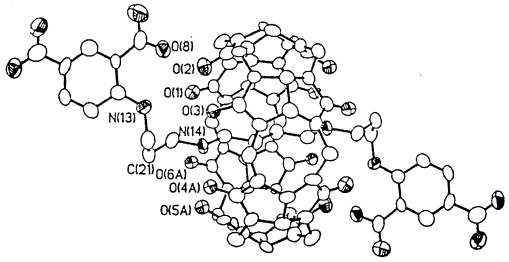


Figure 1. Structure of the rotaxane 3 (dication). Selective interatomic distances (Å): N(14)···O(1) = 4.208(11), N(14)···O(2) = 3.604(11), N(14)···O(3) = 2.987(11), N(14)···O(4A) = 2.822(11), N(14)···O(5A) = 2.977(11), N(14)···O(6A) = 3.895(11).

After numerous unsuccessful attempts the structure of **3** was finally confirmed by X-ray crystallography with help of a CCD-based X-ray diffractometer. An ORTEP drawing of **3**, which has a center of symmetry, is displayed in Figure 1. The rotaxane dication has an expected connectivity. The cavitand deforms moderately to accommodate the spermine thread. Diameter of the cavitand decreases in the direction perpendicular to the mean plane of the guest chain and increases in the direction of the plane upon formation of the rotaxane: the longest and shortest cross-cage diameters of the cavitand in **3** are 10.33(2) and 10.02(2) Å, whereas the average diameter of the 'empty' cavitand is 10.06(1) Å.[6c] The deformation of the portals is also reflected in the distances between two facing oxygen atoms across the portal in the same manner. The two inside amine nitrogen atoms (N14 and N14A) are protonated to form hydrogen bonds with the oxygen atoms at the cucurbituril portals. Distances between N14 and the oxygen atoms, however, indicate that the nitrogen atom forms hydrogen bonds with three of them (O3, O4A, and O5A), but not with the rest (O1, O2 and O6A). The nitrogen atom is located 0.06(2) Å outside the mean plane of the six oxygen atoms. The middle portion of the thread is fully extended; however, the chain changes its direction almost 90° at C21. The nitrogen atom N13 (and N13A) forms a strong hydrogen bond with the *ortho* nitro group on the phenyl ring (N13···O8 = 2.641(11) Å) and a weak one with an oxygen atom (O3) at the portal of the cavitand (N13···O3 = 3.110(11) Å).

Crystals of the pseudorotaxane **4**, in which the both ends of spermine thread are converted to carbamates groups, were formed when diethyl ether was layered over the solution containing the inclusion complex of cucurbituril and spermine, pH of which was adjusted to 8-9 by adding saturated sodium bicarbonate solution.[10] The pseudorotaxane appeared to be produced by the reaction of the terminal amines of spermine moiety of the inclusion complex with bicarbonate. The structure of **4** was determined by X-ray crystallography.[11]

Figure 2 shows the structure of **4**, which also has a center of symmetry. Although the size of the terminal carbamate group may not be large enough as a stopper, but its negative charge

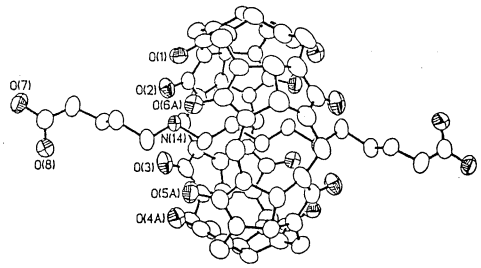


Figure 2. Structure of the pseudorotaxane **4**. Selective interatomic distances (Å): N(14)···O(1) = 2.869(6), N(14)···O(2) = 2.878(6), N(14)···O(3) = 3.180(7), N(14)···O(4A) = 3.961(7), N(14)···O(5A) = 4.257(6), N(14)···O(6A) = 3.347(7).

seems to prevent dethreading effectively. The core structure of **4** is very similar to that of **3**. The cucurbituril cavitand deforms to accommodate the spermine thread in the same manner as in **3**. Strong hydrogen bonding between the internal amine (ammonium) nitrogen atoms and the oxygen atoms at the portals are also evident in **4** . The packing diagram of **4** is shown in Figure 3. One interesting thing to note is that the carbamate groups of a pseudorotaxane molecule forms strong hydrogen bonds with those of adjacent pseudorotaxane molecules (N13···O7A' = O7···N13A' = 2.905(7) Å). The strong intermolecular hydrogen bonds between the terminal groups of the sperminedicarbamate threads link them head-to-tail to form an 1-D 'polymer' in the solid state. This solid structure may be, therefore, viewed as a 'polyrotaxane' in which cucurbituril beads are threaded by 'poly(sperminedicarbamate)'.

In conclusion, we present here a simple, one-step, high-yield synthesis of a rotaxane based on cucurbituril and spermine by taking advantage of the strong tendency of cucurbituril to form host-guest complexes with alkyl diammonium salts. Recent advances in X-ray diffraction technology allowed us to determine the crystal structure of the supramolecular species. This work also demonstrates that cucurbituril may be used as a useful alternative to cyclodextrins in supramolecular chemistry because of its easy synthesis, rigid structure and capability of holding guest molecules. Synthesis and structural studies of polyrotaxanes and other supramolecular species based on cucurbituril are currently in progress in our laboratory.

We acknowledge Korea Science and Engineering Foundation for support of this work. Thanks are due to Professor A. Osuka of Kyoto University for providing us with mass spectral data and to Professor Byeang Hyean Kim for helpful discussions. We are also grateful to Professor S. J. Lippard of Massachusetts Institute of Technology for allowing one of us (K.K.) to collect the X-ray diffraction data for the rotaxane **3**.

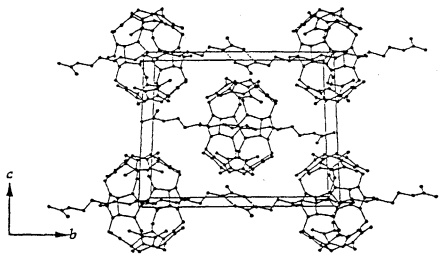


Figure 3. Packing diagram of the pseudorotaxane **4**.

References and Notes

1 G. Schill, *Catenanes, Rotaxanes, and Knots*, Academic Press, New York (1971).
2 D. Philip and J. F. Stoddart, *Synlett*, **1991**, 445.
3 P. L. Anelli, P. R. Ashton, R. Ballardini, V. Balzani, M. Delgado, M. T. Gandolfi, T. T. Goodnow, A. E. Kaifer, D. Philp, M. Pietraszkiewicz, L. Prodi, M. V. Reddington, A. M. Z. Slawin, N. Spencer, J. F. Stoddart, C. Vincent, and D. J. Williams: *J. Am. Chem. Soc.*, **114**, 193 (1992).
4 a) H. Ogino, *J. Am. Chem. Soc.*, **103**, 1303 (1981); b) R. Isnin and A. E. Kaifer, *J. Am. Chem. Soc.*, **113**, 8188 (1991); c) R. S. Wylie and D. H. Macartney, *J. Am. Chem. Soc.*, **114**, 3136 (1992); d) G. Wenz, E. van der Bey, and L. Schmidt, *Angew. Chem. Int. Ed. Engl.*, **31**, 783 (1992).
5 a) A. Harada, J. Li, and M. Kamachi, *Nature*, **356**, 325 (1992); b) A. Harada, J. Li, and M. Kamachi, *J. Am. Chem. Soc.*, **116**, 3192 (1994).
6 a) R. Behrend, E. Meyer, and F. Rusche, Libigs. *Ann. Chem.*, **339**, 1 (1905); b) W. A. Freeman, W. L. Mock, and N.-Y. Shih, *J. Am. Chem. Soc.*, **103**, 7367 (1981); c) W. A. Freeman, *Acta Cryst.*, **B40**, 382, (1984).
7 a) W. L. Mock and N.-Y. Shih, *J. Org. Chem.*, **48**, 3618 (1983); b) W. L. Mock and N.-Y. Shih, *J. Org. Chem.*, **51**, 4440 (1986); c) W. L. Mock and N.-Y. Shih, *J. Am. Chem. Soc.*, **110**, 4706 (1988); d) W. L. Mock and N.-Y. Shih, *J. Am. Chem. Soc.*, **111**, 2697 (1989).
8 Cucurbituril **1** (0.200 g; 0.201 mmol) and spermine tetrahydrochloride **2** (0.055 g; 0.158 mmol) were added to water (3 mL). After 30 min of stirring, undissolved cucurbituril was filtered off. After the pH of the filtrate was raised to ~8 by adding 2,6-lutidine (1 mL), 2,4-dinitrofluorobenzene (0.250 mL; 1.991 mmol) was added. The resulting solution was stirred at room temperature under argon for 21 h. During this time the yellow product precipitated out, which was filtered, washed with water and diethyl ether several times and dried in air (0.226 g, 83 %). ^{1}H NMR (300 MHz, d^6-DMSO) δ 0.44 (4H, b, m), 2.19 (8H, b, m), 3.28 (4H, b, m), 4.02 (4H, b, m), 4.47 (12H, d, J = 14.94Hz), 5.58 (12H, d, J = 14.94 Hz), 5.58 (12H, s), 6.46 (4H, b, m), 7.48 (2H, d, J = 9.96 Hz), 8.26 (2H, dd, J = 2.49 Hz, J = 9.33 Hz), 8.88 (2H, d, J = 2.49 Hz), 9.06 (2H, t, b, s) ^{13}C NMR (DMSO-d^6): δ 23.21, 24.58, 40.29, 44.83, 46.07, 50.64, 69.14, 115.31, 123.40, 129.65, 129.95, 134.79, 148.05, 155.41. FAB MS: m/z 1532 (M-2ClO$_4$-H)$^+$. IR (KBr, cm^{-1}) 3370, 3125, 2941, 2871, 1738, 1605, 1499, 1422, 1302, 1190, 1141, 965, 923, 802, 745, 673. Anal. Calcd for $C_{58}H_{68}N_{32}O_{28}Cl_2 \cdot 5H_2O$: C, 38.22; H, 4.21; N, 24.60%. Found: C, 38.28; H, 4.20; N, 24.80%.
9 Crystal data for **3**: $C_{58}H_{68}N_{32}O_{28}Cl_2 \cdot 4C_3H_7NO \cdot 0.86C_2H_6O \cdot 4H_2O$, monoclinic, *C*2/*c*, *a* = 27.9173(5) Å, *b* = 15.6310(1) Å, *c* = 25.0192(1) Å, β = 111.839(1)°, *V* = 10134.2(2) Å^3, *Z* = 4, *T* = 188 K, Siemens SMART diffractometer with a CCD detector, Mo Kα radiation, Full matrix least square refinement on F^2, *R1* ($I > 2\sigma(I)$) = 0.125, *wR2* (all data) = 0.36.
10 Cucurbituril (0.100 g, 0.100 mmol) and spermine tetrahydrochloride (0.037 g, 0.106 mmol) were added to water (1 mL) and the mixture was stirred for 1 h. The pH of the mixture was adjusted to 8-9 by adding NaHCO$_3$. Diethyl ether was allowed to diffuse into the solution to yield colorless crystals of **4** suitable for X-ray work (0.048 g, 37 %). FAB MS: m/z 1200.19 (M-2CO$_2$ + H)$^+$. IR (KBr, cm^{-1}) 3423, 3391, 3143, 2941, 2871, 1733, 1569 (carbamate), 1480, 1417, 1378, 1327, 1290, 1237, 1191, 1147, 965, 819, 802, 761, 676. Anal. Calcd for $C_{48}H_{62}O_{16}N_{28} \cdot 13H_2O$: C, 37.89; H, 5.78; N, 25.78%. Found: C, 37.94; H, 5.25; N 25.52%.
11 Crystal data for **4**: $C_{48}H_{62}N_{28}O_{16} \cdot 14.37H_2O$, monoclinic, $P2_1/c$, *a* = 12.779(3) Å, *b* = 18.293(4) Å, *c* = 15.710(3) Å, β = 111.84(3)°, *V* = 3408.9(12) Å^3, *Z* = 2, *T* = 295 K, Enraf-Nonius CAD4 diffractometer, Mo Kα radiation, Full matrix least square refinement on F^2, *R1* ($I > 2\sigma(I)$) = 0.095, *wR2* (all data) = 0.31.