J|A|C|S
COMMUNICATIONS

Published on Web 11/13/2003

Self-Assembled Nanotubes that Reversibly Bind Acetic Acid Guests

Linda S. Shimizu,* Andrew D. Hughes, Mark D. Smith, Matthew J. Davis, B. Paul Zhang, Hans-Conrad zur Loye, and Ken D. Shimizu

Department of Chemistry and Biochemistry, University of South Carolina, Columbia, South Carolina 29208

Received June 4, 2003; E-mail: shimizul@mail.chem.sc.edu

There is great interest in the design and synthesis of hollow nanotubular structures. Such structures have a wide range of applications in biology, chemistry, and material science.[1] We have previously reported a small bis-urea macrocycle that is readily synthetically accessible and that self-assembles into columnar structures via urea-urea hydrogen bonding.[2] We report, herein, the synthesis and assembly of a larger bis-urea macrocycle **1** that assembles into columnar nanotubes containing a sizable cavity. This purely organic nanotube is held together primarily by hydrogen bonding and yet shows remarkable thermal stability up to 180 °C in the presence and absence of acetic acid guest. This enables the nanotube to be used as reusable organic zeolite.

The use of rigid macrocycles to form porous materials has a number of advantages over the use of smaller linear building blocks. The macrocycles inhibit interpenetration and lead to a cavity of predetermined dimensions. Variation of the size and shape of the rigid spacers could lead to "tunable" cavities, designed to bind specific guests. Some beautiful examples of this strategy include Ghadiri's cyclic peptides,[3] Stang's molecular squares,[4] Moore's macrocyclic polyphenyleneethynylenes,[5] and Dory's nanotubes.[6]

A key design element was to ensure that the macrocycles would stack directly on top of each other to form a cavity.[7] This was accomplished by incorporating two urea groups into the macrocyclic structure to form strong 3-centered intermolecular hydrogen bonds.[8,9] The rigid diphenyl ether units of **1** inhibit intramolecular hydrogen bond formation and also prevent collapse of the interior cavity.

Bis-urea **1** was readily synthesized in two steps from the dibromide **2**. The urea functionality was introduced as the protected *tert*-butyl triazone **3** to prevent over-alkylation and premature self-assembly. The improved solubility of protected macrocycle **4** facilitated its isolation and its characterization by X-ray crystallography. Deprotection with diethanol amine in methanol yielded bis-urea macrocycle **1** (Figure 1 and Scheme 1).

Clear colorless needles suitable for X-ray analysis were obtained upon slow cooling of **1** (120 to 25 °C at 1 deg/h) in a sealed tube with glacial acetic acid (20 mg/30 mL). The crystal structure of **1** revealed the expected molecular and extended structure (Figure 2). The macrocycles were stacked together by intermolecular urea−urea hydrogen bonds and by edge-to-face π-stacking between the diphenyl ether linkers. Individual tubes (Figure 2b) show urea carbonyl groups aligned in parallel but opposite orientations, presumably to minimize the dipole moment. The urea−urea hydrogen-bonding distances range from 2.852 to 3.050 Å. The individual molecular columns in the crystal consist of both possible *transoid* urea group orientations averaged throughout the crystal in the ratio 0.65:0.35, while the −PhOPh− linkers are well-ordered. Most importantly, the nanotube displays a sizable rectangular cavity that is filled with a channel of well-ordered acetic acid dimers.

The stability of the self-assembled network in the absence of the guest was tested by TGA (Figure 3). A weight loss of 11.61% was measured occurring between 30 and 90 °C, consistent with the loss of all of the acetic acid guest (calculated weight loss, 10.56%). ^{1}H NMR of the dissolved crystals in DMSO-d_6 confirmed that the nanotubes were empty of guest. The empty crystals appeared to be stable and showed no further weight loss up to a

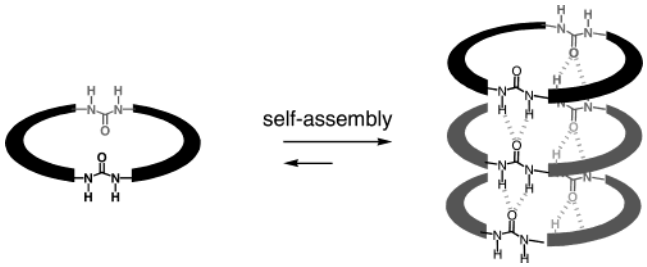
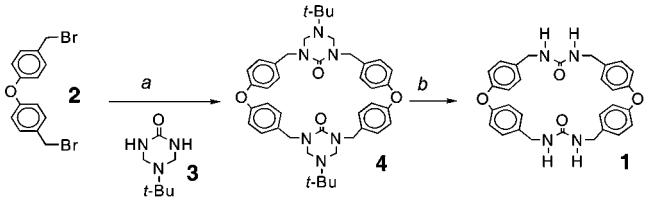


Figure 1. Schematic representation of the self-assembly of bis-urea **1** into a nanotube.

Scheme 1 [a]



[a] Reagents and conditions: (a) *tert*-butyl triazone **3**, NaH, THF, 20%. (b) 20% diethanol amine, MeOH, reflux, 85%.

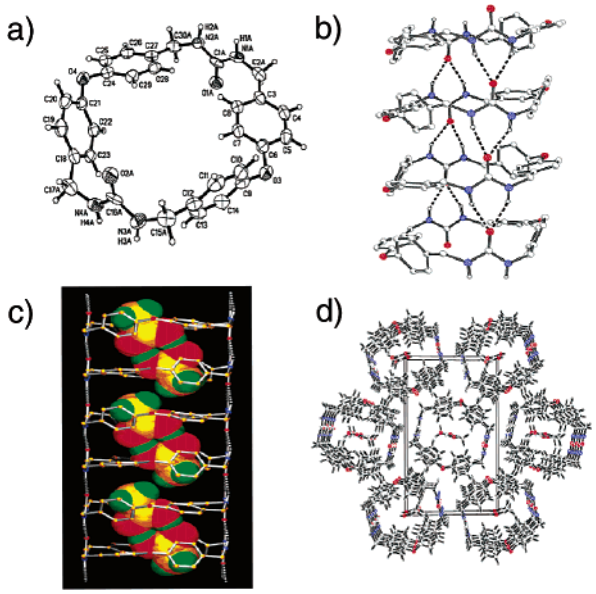


Figure 2. Various views of the X-ray structure of **1**·AcOH: (a) molecular structure with AcOH omitted, (b) assembled nanotube with guest omitted and (c) guest included, and (d) packing diagram of the nanotubes looking down the tube axis.

10.1021/ja036515i CCC: $25.00

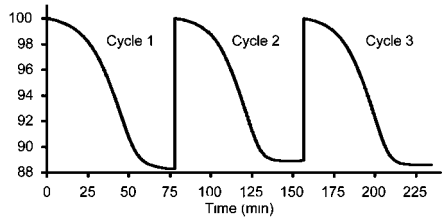


Figure 3. Three successive cycles of TGA of assembly **1**·AcOH (23 to 100 °C at 1 deg/min), followed by reloading of acetic acid guest.

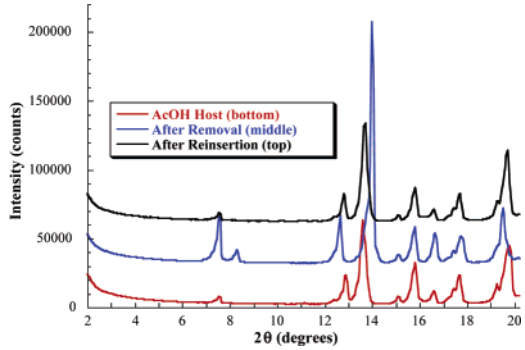


Figure 4. PXRD patterns for assembled **1** with encapsulated AcOH (bottom). Assembled **1** after AcOH removal by heating to 120 °C (middle). Assembled **1** after AcOH reinsertion by treatment with AcOH vapor (top).

temperature of 150 °C, and the white crystals retained their shape and showed no sign of cracking. We then sought to rebind the acetic acid guest by treatment of the empty self-assembled network with acetic acid. The crystals were exposed to acetic acid vapor in a sealed vessel for 72 h and then reexamined by TGA (Figure 3, cycle 2). A nearly identical weight loss curve was observed (11.02% weight loss). Repetition of acetic acid guest removal and rebinding of the same crystals a third time established that the inclusion behavior is reversible and that the channels retain their inclusion ability over time (Figure 3, cycle 3).

Powder X-ray diffraction (PXRD) provided further evidence for the structural stability of the empty nanotube assembly and the reversibility of the binding process. The guest-filled crystals were ground to a powder and examined by PXRD (Figure 4). The guest was then removed by heating to 120 °C for 1.5 h, and the powder was reexamined by PXRD. The PXRD pattern of empty assembly shows a slightly different but well-defined structure. Upon treatment of the evacuated solid with acetic acid vapor, the powder exhibits a PXRD pattern with peak positions and intensities nearly identical to the original acetic acid bound structure.

The single crystal data was used to calculate PXRD patterns for the AcOH bound and evacuated solids. Not surprisingly, the calculated PXRD for the bound material closely matched the observed PXRD, supporting the hypothesis that the bulk material shows a single phase product that has a similar structure to the single crystal. For the evacuated solid, a PXRD was calculated simply by omitting the acetic acid guests from the single crystal X-ray structure. Again this calculated structure is very close to the experimentally observed PXRD of the empty assembly, supporting the hypothesis that the evacuated network is structurally similar to the filled network and that the matrix maintains its integrity with empty channels. Indeed, only a handful of materials has been observed that have a similarly robust lattice structures in the presence and absence of guests.[10]

In conclusion, a large, highly symmetric bis-urea macrocycle **1** was easily synthesized from commercially available materials. The NMR, TGA, and X-ray diffraction data show conclusively that **1** assembles to form columnar nanotubes, which is driven by the strong urea−urea self-association and π-stacking of the rigid spacers. The formation of these noncovalent porous solids creates a robust cavity that can reversibly bind and exchange guest acetic acid molecules. Their modular construction from rigid spacers and protected ureas should enable the large-scale synthesis of similar tubular materials and enhance their viability in practical applications. We are currently probing the affinity and binding specificity of the cavity of **1**, and preliminary studies show that the nanotubes can reversibly bind a wide range of guest molecules just like ordinary molecular sieves. We will report these data in due course.

Acknowledgment. This work was supported by the NSF (Grant No. 9973132.).

Supporting Information Available: Detailed descriptions of the synthesis and characterization of key compounds and crystal data, atomic coordinates, bond lengths and angles of **1** and **4** (CIF), and experimental and calculated PXRD of filled and empty **1** (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) Bong, D. T.; Clark, T. D.; Granja, J. R.; Ghadiri, M. R. *Angew. Chem., Int. Ed.* **2001**, *40*, 988. (b) Ranganathan, D.; Lakshmi, C.; Haridas, V.; Gopikumar, M. *Pure Appl. Chem.* **2000**, *72*, 365.
(2) Shimizu, L. S.; Smith, M. D.; Hughes, A. D.; Shimizu, K. D. *Chem. Commun.* **2001**, 1592−1593.
(3) Ghadiri, M. R.; Granja, J. R.; Buehler, L. K. *Nature* **1994**, *369*, 301.
(4) Stang, P. J.; Olenyuk, B. *Acc. Chem. Res.* **1997**, *30*, 502.
(5) (a) Zhang, J.; Moore, J. S. *J. Am. Chem. Soc.* **1992**, *114*, 9701. (b) Moore, J. S. *Acc. Chem. Res.* **1997**, *30*, 402.
(6) Gauthier, D.; Baillargeon, P.; Drouin, J.; Dory, Y. L. *Angew. Chem., Int. Ed.* **2001**, *40*, 4635.
(7) For other examples utilizing ureas to direct the self-assembly of macrocyclic structures, see: (a) Ranganathan, D.; Kurur, S.; Madhusudanan, K. P.; Karle, I. L. *Tetrahedron Lett.* **1997**, *38*, 4659. (b) Semetey, V.; Didierjean, C.; Briand, J. P.; Aubry, A.; Guichard, G. *Angew. Chem., Int. Ed.* **2002**, *41*, 1895. (c) Shimizu, K. D.; Rebek, J. *Proc. Natl. Acad. Sci. U.S.A.* **1995**, *92*, 12403.
(8) (a) Etter, M.; Urbanczyk-Lipkowska, Z.; Zia-Ebrahimi, M.; Panunto, T. W. *J. Am. Chem. Soc.* **1990**, *112*, 8415. (b) Etter, M. C.; Panunto, T. W. *J. Am. Chem. Soc.* **1988**, *110*, 5896.
(9) (a) Zhao, X. Q.; Chang, Y. L.; Fowler, F. W.; Lauher, J. W. *J. Am. Chem. Soc.* **1990**, *112*, 6627. (b) Schauer, C. L.; Matwey, E.; Fowler, F. W.; Lauher, J. W. *J. Am. Chem. Soc.* **1997**, *119*, 10245. (c) Hollingsworth, M. D.; Brown, J. E.; Satarsiero, B. D.; Huffman, J. C.; Goss, C. R. *Chem. Mater.* **1994**, *6*, 1227. (d) Hollingsworth, M. D.; Brown, M. E.; Santarsiero, B. D.; Huffman, J. C.; Goss, C. R. *Chem. Mater.* **1994**, *6*, 1227. (e) Carr, A. J.; Melendez, R.; Geib, S. J.; Hamilton, A. D. *Tetrahedron Lett.* **1998**, *39*, 7447. (f) van Esch, J.; Schoonbeek, F.; de Loos, M.; Kooijman, H.; Spek, A. L.; Kellogg, R. M.; Feringa, B. L. *Chem.−Eur. J.* **1999**, *5*, 937−950.
(10) (a) Eddaoudi, M.; Moler, D. B.; Li, H. L.; Chen, B. L.; Reineke, T. M.; O'Keeffe, M.; Yaghi, O. M. *Acc. Chem. Res.* **2001**, *34*, 319. (b) Cui, Y.; Lee, S. J.; Lin, W. *J. Am. Chem. Soc.* **2003**, 6014. (c) Endo, K.; Sawaki, T.; Koyanagi, M.; Kobayashi, K.; Masuda, H.; Aoyama, Y. *J. Am. Chem. Soc.* **1995**, *117*, 8341−8352.

JA036515I