Main-Chain Calixarene Polymers: Conformational Effects on Polymerization

Yong Yang and Timothy M. Swager*

Department of Chemistry and Institute for Soldier Nanotechnologies, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139

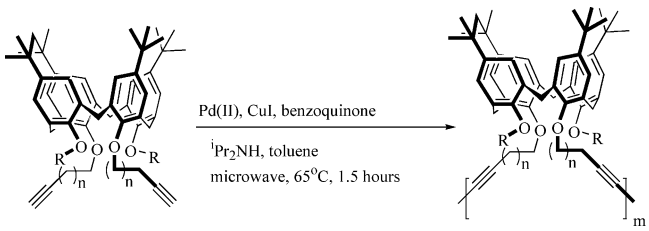
Received December 8, 2005

Revised Manuscript Received January 28, 2006

Calix[4]arenes are cornerstones of supramolecular chemistry[1] and have been broadly utilized in host−guest chemistry,[2] directed assembly,[3] and chemosensors.[4] One of their features is their conformational flexibility. Calix[4]arenes suitably alkylated on the lower rim are able to undergo conformational changes that involve ring flips (between cone, partial cone, and 1,3-alternate conformers) in addition to subtle transitions between pinched-cone and pinched-cone hinge conformations.[5] Covalent linkages of calix[4]arenes in a polymer main chain (i.e., to polymerize calix[4]arenes through their 1,3-positions at either lower rims or upper rims) are envisioned to use these individual conformational changes to achieve sensory responses[6] and/or actuatory behavior.[7] In our group, electroactive linkages of calixarenes through upper rims have been accomplished by electrochemical polymerization.[8] To our knowledge, only two lower rim linkage polymers have been reported previously.[9,10] Both types of the copolymers had relatively low molecular weights, and one[10] suffered from low incorporation of calixarene in the polymer backbone. We have endeavored to produce polymers using acetylenic coupling due to its high atom economy[11] and the ability to build rigid and sterically undemanding molecular structures.[12] Herein, we use an improved acetylenic homocoupling[13] to construct polymers with bulky and conformationally active blocks.

As shown in Scheme 1, parent *p-tert*-butylcalix[4]arene **2c** was directly alkylated with terminal alkynes **1** or propargyl bromide to furnish monomers **3c** and **4c**, respectively. In **3c** and **4c**, the cone conformations were fixed by the remaining two free phenols through the hydrogen bonding with neighboring phenolic oxygen atoms. Monomer precursors **2a** and **2b**, which are protected at the two alternate phenols,[14] were further functionalized by polymerizable arms. Monomers **3b** and **4b** are mixtures of conformers in dynamic equilibrium because the relatively small methyl protecting groups allow the aryl rings to freely rotate through the calixarene annulus.[15] Bulky benzyl groups fix the conformations of **3a** and **4a**, and their ratios of the partial cone (paco) conformer and cone conformer are influenced by the synthetic conditions (see Supporting Information). The paco/cone preference partially results from template effects of base counterions.[16] Pure cone and paco conformers were obtained after column chromatography or recrystallization. The cone and paco conformations are confirmed by the well-established ^{1}H NMR patterns of the bridge methylene protons.[1a] For example, **3a**-cone shows one pair of doublets (4.41 and 3.12 ppm) with a coupling constant of 12.4 Hz and a difference of 1.29 ppm between the high- and low-field protons. **3a**-paco gives two pairs of doublets, one pair at 4.08 and 2.99 ppm with a coupling constant of 12.6 Hz and the other pair at 3.67 and 3.60 ppm with a coupling constant of 12.7 Hz.

Table 1. Synthesis of Polymers



		polymer[a]				oligomer[a]	
entry	monomer	M_n (kDa)	M_w (kDa)	PDI	yield (%)	M_p (kDa)	yield (%)
1	**3a**-cone					4	21
2	**3a**-paco	106	238	2.25	88	3	trace
3	**4a**-cone					5	74
4	**4a**-paco	46	61	1.31	67	4	8
5	**3b**					10	90
6	**4b**					3	80
7	**3c**					3	25
8	**4c**						

[a] Molecular weights and PDI were determined by GPC (polystyrene standards). M_p: peak value.

During the screening of monomers, we found that **4c** and **3c** either did not react (Table 1, entry 8) or only afforded oligomers (entry 7). This effect is probably due to the interference of phenolic protons with catalytic intermediates. Monomers **3b** and **4b** also gave oligomers (entries 5 and 6). We considered that the conformational diversity of **3b** and **4b** prevented them from forming polymers. Thus, we turned to a protect−freeze−deprotect route to isolate **4a** in an exclusive cone conformation. However, only oligomers were obtained under a variety of reaction conditions (e.g., entry 3), and similar results were obtained with **3a**-cone wherein a spacer was inserted between the acetylene and the calixarene to facilitate coupling (entry 1).

Fortunately, by changing from cone to paco conformation, the polymerizations were dramatically accelerated (entries 2 and 4). To rule out that the high molecular weights were the result of cross-linking from a trace trifunctional impurity, we subjected **3a**-paco (after column chromatography and recrystallization) to HPLC purification. The polymerization of the ultrahigh-purity **3a**-paco produced similar results. The high-molecular-weight poly(**3a**-paco) forms gels that can be completely redissolved with $CHCl_3$ after sonication.

The high reactivity of paco monomers is understood by considering the mechanism of Pd-catalyzed acetylenic coupling. The reductive elimination requires two calixarene moieties on the Pd center to adopt a cis configuration.[17] In the cone conformation, steric hindrance derived from the shape makes the cis configuration at the Pd center highly unfavorable. Reshaping the cuplike cone conformer to a pseudo-tubular paco conformer results in reduced steric effects (Figure 1). Single crystals of the three monomers were grown, and the X-ray crystal structures of **4a**-paco and **3a**-cone are shown in Figure 1 (**3a**-paco is shown in the Supporting Information). In the paco conformer, one aryl ring with the terminal alkyne is flipped and the *t*-Bu group is partially sandwiched between the two Bn rings, and this conformation is likely by CH···π interactions. This pinched paco conformation resembles a tubule with the

* Corresponding author. E-mail: tswager@mit.edu.

10.1021/ma052630x CCC: $33.50 © 2006 American Chemical Society
Published on Web 02/16/2006

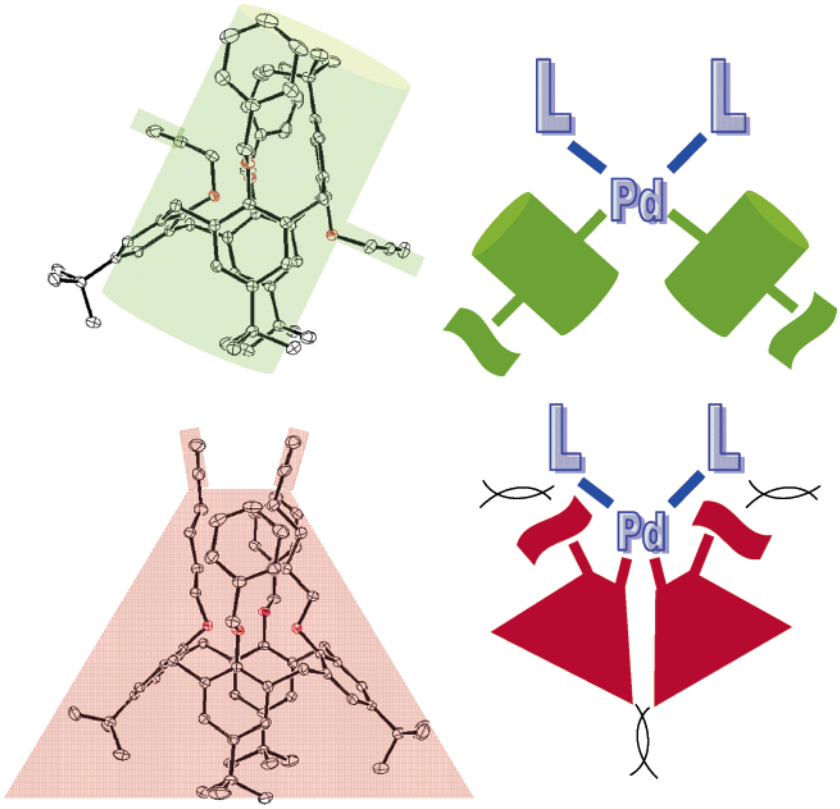
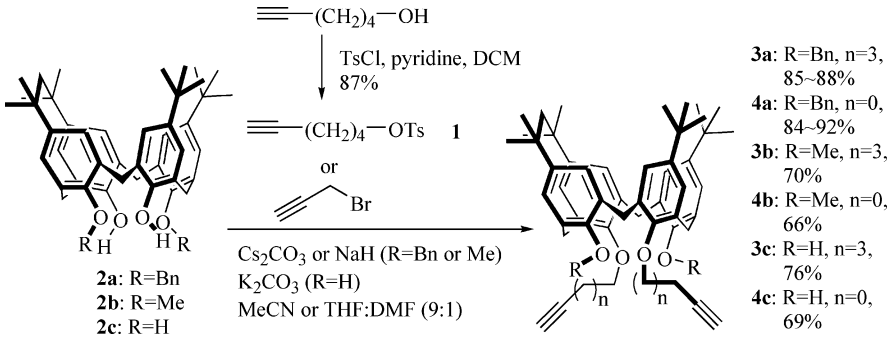


Figure 1. ORTEP[20] drawings of **4a**-paco (upper left) and **3a**-cone (bottom left). Exaggerated cartoons showing proposed mechanism (right).

Scheme 1. Synthesis of Monomers



two polymerizable arms extending out from its midsection. The elongated geometry is favorable for polymer growth. From the X-ray structure the cone conformer may be best characterized as a pinched cone conformation. Despite the two longer arms of **3a**-cone that extend the acetylenes from the body of calixarene, they are still too close and are inaccessible to the catalytic center. We also have considered that the inability of the cone conformers to produce high polymer may also be the result of a propensity for forming cyclic oligomers. In pursuit of high polymer from the cone conformers we also investigated Pd-free Cu-coupling conditions (see Supporting Information). In this process a trans-like geometry about the dimeric Cu−acetylene catalytic intermediate is favored.[18] Considering their structures, we expected the cone conformers to encounter less steric hindrance in this scenario. Unfortunately, all attempts with classical Cu−acetylene coupling protocols gave only oligomers, and it is unclear whether the low polymerization efficacy is due to the sterics of the cone conformation or the fact that the catalytic conditions which are known to be inferior to the those reported herein.[13] To further investigate the effects of the relative sterics, we investigated polymerizations based on Sonogashira coupling (with 1,4-diiodobenzene, see Supporting Information). In these studies **4a**-paco did not show any significant advantages over **4a**-cone. Hence, this is additional evidence to support the proposed role of the conformations because in Sonogashira reactions the calixarene acetylene couples with a sterically undemanding 1,4-diiodobenzene comonomer.

All of our main-chain calixarene polymers are readily soluble in common organic solvents. The diacetylenes can provide access into other polymer structures, and they can be hydrogenated to give butane units polymer backbone by treatment with *p*-toluenesulfonhydrazide and tripropylamine.[21] The benzyl (Bn) protecting groups can be removed under heating with TMSBr.[22] It is worth mentioning that conventional hydrogenation (H_2, Pd/C) could neither reduce the alkynes nor remove the benzyl groups, probably because the calixarene polymers have difficulty in interacting with the catalytic surface.

In summary, we have synthesized high-molecular-weight main-chain calixarene homopolymers via linkages on lower rims. We have found that the calixarene conformation has a profound influence on the polymerization. Our synthetic methodology can be applied to the polymerizations of other sterically demanding and conformationally flexible monomers. Main-chain calixarene polymers linked through the lower rims present new

opportunities to create efficient separations, and materials for sensing and actuation, as a result of their dynamic receptor properties.

Acknowledgment. This work was supported by the U.S. Army through the Institute for Soldier Nanotechnologies, under Contract DAAD-19-02-0002 with the U.S. Army Research Office. We thank Dr. Peter Müller for X-ray diffraction experiments.

Supporting Information Available: Detailed description of experimental procedures, X-ray structure of **3a**-paco, and three crystallographic information files. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) (a) Gutsche, C. D. In *Calixarenes Revisited, Monographs in Supramolecular Chemistry*; Stoddart, J. F., Ed.; The Royal Society of Chemistry: Cambridge, UK, 1998. (b) *Calixarenes: A Versatile Class of Macrocyclic Compounds*; Vicens, J., Bohmer, V., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1991. (c) *Calixarenes in Action*; Mandolini, L., Ungaro, R., Eds.; Imperial College Press: London, UK, 2000. (d) Ikeda, A.; Shinkai, S. *Chem. Rev.* **1997**, *97*, 1713.

(2) (a) Atwood, J. L.; Barbour, L. J.; Jerga, A. *Science* **2002**, *296*, 2367. (b) Atwood, J. L.; Barbour, L. J.; Jerga, A.; Schottel, B. L. *Science* **2002**, *298*, 1000. (c) Ishii, Y.; Takenaka, Y.; Konishi, K. *Angew. Chem., Int. Ed.* **2004**, *43*, 2702.

(3) (a) Orr, G. W.; Barbour, L. J.; Atwood, J. L. *Science* **1999**, *285*, 1049. (b) Corbellini, F.; Mulder, A.; Sartori, A.; Ludden, M. J. W.; Casnati, A.; Ungaro, R.; Huskens, J.; Crego-Calama, M.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **2004**, *126*, 17050. (c) Castellano, R. K.; Nuckolls, C.; Rebek, J., Jr. *J. Am. Chem. Soc.* **1999**, *121*, 11156.

(4) (a) Yu, H.-h.; Pullen, A. E.; Büchel, M. G.; Swager, T. M. *Angew. Chem., Int. Ed.* **2004**, *43*, 3700. (b) Kim, S. K.; Lee, S. H.; Lee, J. Y.; Lee, J. Y.; Bartsch, R. A.; Kim, J. S. *J. Am. Chem. Soc.* **2004**, *126*, 16499.

(5) Scheerder, J.; Vreekamp, R. H.; Engbersen, J. F. J.; Verboom, W.; van Duynhoven, J. P. M.; Reinhoudt, D. N. *J. Org. Chem.* **1996**, *61*, 3476.

(6) (a) Swager, T. M. *Acc. Chem. Res.* **1998**, *31*, 201. (b) McQuade, D. T.; Pullen, A. E.; Swager, T. M. *Chem. Rev.* **2000**, *100*, 2537.

(7) (a) Scherlis, D. A.; Marzari, N. *J. Am. Chem. Soc.* **2005**, *127*, 3207. (b) Yu, H.-H.; Swager, T. M. *IEEE J. Oceanic Eng.* **2004**, *29*, 692.

(8) Yu, H.-H.; Xu, B.; Swager, T. M. *J. Am. Chem. Soc.* **2003**, *125*, 1142.

(9) Kenis, P. J. A.; Noordman, O. F. J.; van Hulst, N. F.; Engbersen, J. F. J.; Reinhoudt, D. N.; Hams, B. H. M.; van der Vorst, C. P. J. M. *Chem. Mater.* **1997**, *9*, 596.

(10) Memon, S.; Oguz, O.; Yilmaz, A.; Tabakci, M.; Yilmaz, M.; Ertul, S. *J. Polym. Environm.* **2001**, *9*, 97.

(11) Trost, B. M. *Science* **1991**, *254*, 1471.

(12) Siemsen, P.; Livingston, R. C.; Diederich, F. *Angew. Chem., Int. Ed.* **2000**, *39*, 2632.

(13) Williams, V. E.; Swager, T. M. *J. Polym. Sci., Part A: Polym. Chem.* **2000**, *38*, 4669.

(14) Dijkstra, P. J.; Brunink, J. A. J.; Bugge, K. E.; Reinhoudt, D. N.; Harkema, S.; Ungaro, R.; Ugozzoli, F.; Ghidini, E. *J. Am. Chem. Soc.* **1989**, *111*, 7567.

(15) Pitarch, M.; Browne, J. K.; McKervey, M. A. *Tetrahedron* **1997**, *53*, 16195.

(16) Iwamoto, K.; Fujimoto, K.; Matsuda, T.; Shinkai, S. *Tetrahedron Lett.* **1990**, *31*, 7169.

(17) Gillie, A.; Stille, J. K. *J. Am. Chem. Soc.* **1980**, *102*, 4933.

(18) Marsden, J. A.; Miller, J. J.; Shirtcliff, L. D.; Haley, M. M. *J. Am. Chem. Soc.* **2005**, *127*, 2464.

(19) Kappe, C. O. *Angew. Chem., Int. Ed.* **2004**, *43*, 6250.

(20) Farrugia, L. J. *J. Appl. Crystallogr.* **1997**, *30*, 565.

(21) Beck, J. B.; Kokil, A.; Ray, D.; Rowan, S. J.; Weder, C. *Macromolecules* **2002**, *35*, 590.

(22) Groenen, L. C.; van Loon, J. D.; Verboom, W.; Harkema, S.; Casnati, A.; Ungaro, R.; Pochini, A.; Ugozzoli, F.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1991**, *113*, 2385.

MA052630X