Efficient, Zirconocene-Mediated Cyclotrimerization and Cyclotetramerization of Me₃SiC≡CC₆H₄C₆H₄C≡CSiMe₃ to Unsaturated Macrocycles
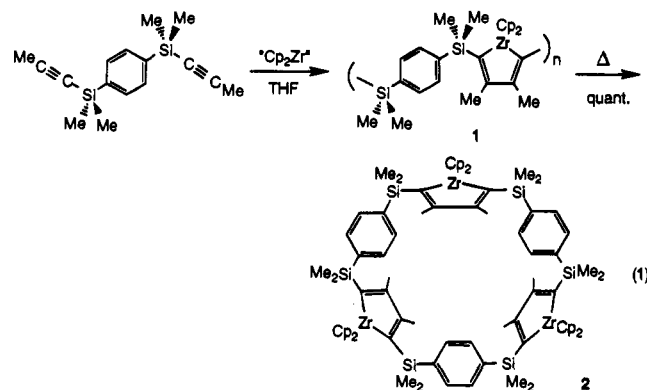
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Macrocycles containing electron-delocalized backbones have attracted considerable attention in recent years.[1] Potential applications for such macrocycles include the combined use of receptor and electron-transport properties in design of devices for molecular sensing or chemical separation.[1a−f,2] In this context, conjugated macrocycles represent intriguing building blocks for construction of solid-state materials with nanoporous networks. A major obstacle inhibiting development of advanced materials based on functionalized macrocycles is the limited number of convenient, versatile, and high-yield synthetic routes, since preparations for macrocycles are generally associated with low yields, multiple steps, and difficult separations.

We have previously reported the zirconocene-mediated polymerization and cyclotrimerization of 1,4-MeC≡C(Me₂Si)-C₆H₄(SiMe₂)C≡CMe, according to eq 1.[3] Polymer **1** and macrocycle **2** are formed in extremely high yield and may be derivatized via reactions of the Zr−C bonds. In further studies we have found that this simple procedure provides a generally convenient, chemically versatile, and highly efficient route to macrocycles. Here we report the application of this strategy to the synthesis of macrocycles with unsaturated carbon backbones.

(1)

Generation of a slight excess of "Cp₂Zr" (by addition of ⁿBuLi to Cp₂ZrCl₂)[4] in the presence of 1,4-Me₃SiC≡

CC₆H₄C₆H₄C≡CSiMe₃ (0.54 M, THF solution, −78 °C to room temperature) resulted in formation of macrocycles **3** and **4** in a combined yield of 85% (Scheme 1).[5] The tetramer **4** was readily separated from the mixture (in 40% yield) by extraction with hexane. Trimer **3** was then extracted into hot toluene and crystallized by concentration and cooling. The thermodynamic product of the reaction is **3**, as shown by its quantitative conversion from **4** in refluxing THF. The yield of **3** was increased to 90% by employing more dilute conditions (0.05 M of the diyne) and heating the reaction mixture to reflux for 24 h.

Air-sensitive, yellow crystals of **3** from THF contain 6 equiv of solvent molecules per macrocycle.[6] None of the solvent molecules are included in the macrocycle cavity, and the disk-like macrocycles (with coplanar zirconacyclopentadiene rings) are packed in a herringbone fashion in the crystal. Bond distances and angles within the rings are unexceptional. The molecules have crystallographic C_2 symmetry, and the biphenylene groups are oriented such that they are roughly perpendicular to the plane of the macrocycle. This molecular shape is similar to that observed for related hexadehydro[18]-annulenes.[7]

X-ray quality crystals of **4**, obtained by cooling a diethyl ether/pentane solution, contain 6 equiv of pentane molecules per macrocycle.[8] The molecules have a folded, COT-like geometry similar to that proposed for Sondheimer's octadehydro-[24]annulene;[7b,9] however, the folding in **4** is rather extreme (fold angle defined by the angle between Zr₃ planes is 31.3°). This highly "collapsed" shape may be attributed (at least partially) to the relatively sharp C(biphenylene)−C(diene)−C(diene) angles of ca. 112°. Steric interactions between biphenylene substituents on the ZrC₄ rings lead to roughly parallel alignment of all the phenylene groups and a distortion of the molecule away from D_{2d} symmetry (the molecule possesses crystallographic D_2 symmetry), resulting in two chemically inequivalent biphenylene groups. Ring strain in the tetramer is evident in slight buckling of pairs of symmetry-equivalent biphenylene groups, such that their C₆H₄ groups intersect at angles of 5.6 and 9.2°.

To help evaluate the extent of delocalization in these oligomeric species, the monozirconium complex 2,5-bis(trimethylsilyl)-3,4-bis(biphenyl)zirconacyclopentadiene was prepared by zirconocene coupling of p-C₆H₅C₆H₄C≡CSiMe₃. This compound exhibits a λ_{max} value of 266 nm, which is bathochromically shifted on going to the trimer **3** (λ_{max} = 288 nm). Tetramer **4** appears to be less delocalized (λ_{max} = 276 nm), and this may be attributed to the distortion of biphenyl groups described above.

The ¹H NMR spectrum of **3** contains a singlet for the Cp groups and two resonances for the biphenyl groups over the

(1) (a) Vögtle, F. *Cyclophane Chemistry*; John Wiley & Sons Ltd.: Chichester, West Sussex, 1993. (b) Diederich, F.; Rubin, Y. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 1101. (c) Diederich, F. *Nature* **1994**, *369*, 199. (d) Zhang, J.; Pesak, D. J.; Ludwick, J. L.; Moore, J. S. *J. Am. Chem. Soc.* **1994**, *116*, 4227. (e) Venkataraman, D.; Lee, S.; Zhang, J.; Moore, J. S. *Nature* **1994**, *371*, 591. (f) Bunz, U. H. F. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1073. (g) Bissell, R. A.; Cordova, E.; Kaifer, A. E.; Stoddart, J. F. *Nature* **1994**, *369*, 133. (h) Amabilino, D. B.; Stoddart, J. F.; Williams, D. J. *Chem. Mater.* **1994**, *6*, 1159. (i) Romero, M. A.; Fallis, A. G. *Tetrahedron Lett.* **1994**, *35*, 4711. (j) Walter, C. J.; Sanders, J. K. M. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 217.

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(4) (a) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829. (b) Takahashi, T.; Swanson, D. R.; Negishi, E. *Chem. Lett.* **1987**, 623. (c) Buchwald, S. L.; Watson, B. T.; Huffman, J. C. *J. Am. Chem. Soc.* **1987**, *109*, 2544.

(5) Experimental details and characterization data are given in the supporting information.

(6) Crystal data for **3**·6THF: C₁₂₀H₁₅₆Si₆O₆Zr₃, tetragonal; P4₁2₁2, a = 14.597(2) Å, c = 53.461(13) Å, V = 11391(7) Å³, Z = 4, D_calcd = 1.25 g cm⁻³, μ(Mo Kα) = 3.8 cm⁻¹, T = −98 °C. The final residuals for 294 parameters refined against the 5095 accepted data (F² > 3σ(F²)) were R = 8.5%, R_w = 9.1%, and GOF = 2.82.

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(8) Crystal data for **4**·6C₆H₁₂: C₁₅₈H₂₀₄Si₈Zr₄, orthorhombic; Pnnn, a = 17.335(3) Å, b = 20.337(4) Å, c = 21.271(4) Å, V = 7499(4) Å³, Z = 2, D_calcd = 1.19 g cm⁻³, μ(Mo Kα) = 3.7 cm⁻¹, T = −93 °C. The final residuals for 188 parameters refined against the 1252 accepted data (F² > 3σ(F²)) were R = 9.0%, R_w = 9.1%, and GOF = 2.58.

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Scheme 1
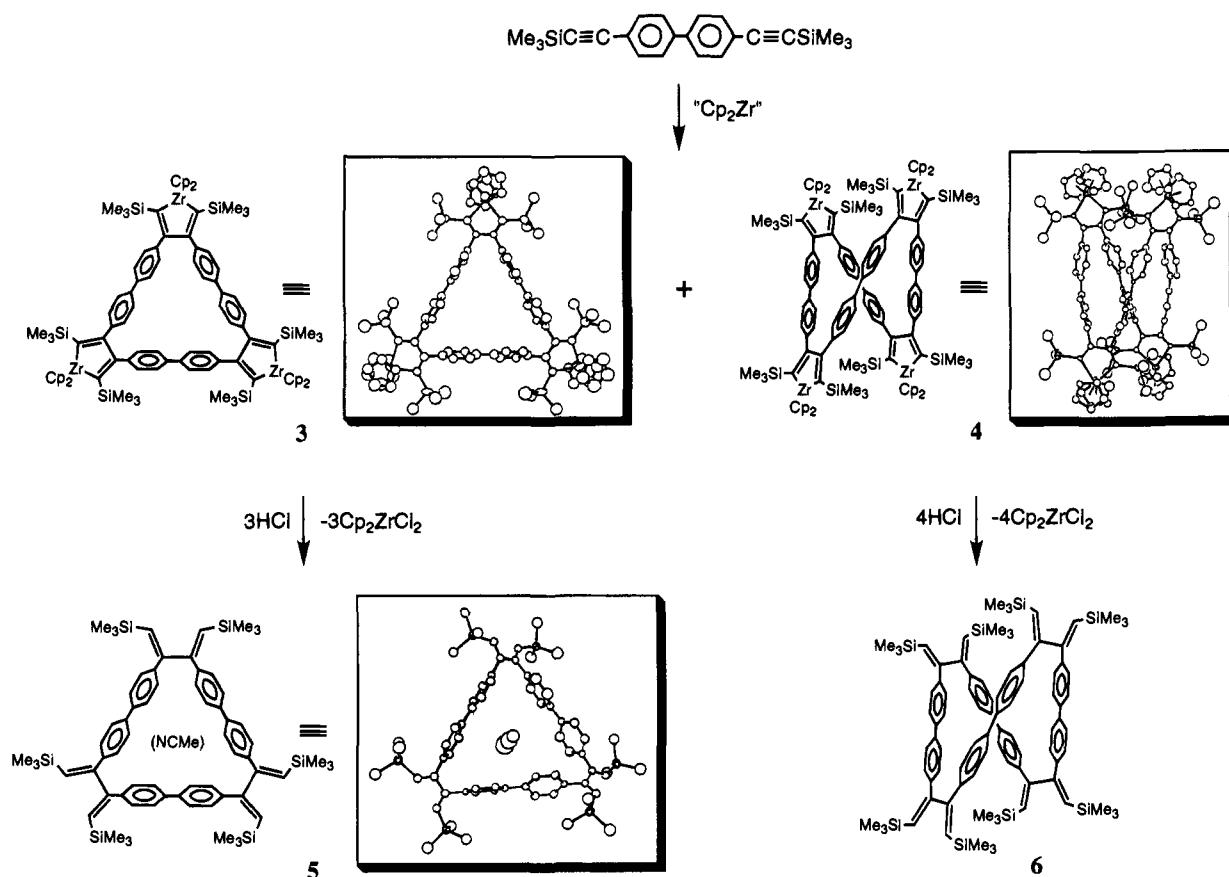
temperature range −80 to 70 °C. In contrast, tetramer **4** exhibits NMR spectra that are consistent with its solid state structure (two sets of Cp and biphenyl resonances) only at low temperature. Coalescence of the Cp (30 °C; $\Delta G^{\ddagger} = 15$ kcal mol^{-1}) and biphenyl (37 °C; $\Delta G^{\ddagger} = 15$ kcal mol^{-1}) resonances is unaffected by the presence of 5 equiv of THF, which indicates that a mechanism involving retrocycloaddition of alkynyl units is unlikely.[3] It would therefore appear that exchange of the Cp ("inner" and "outer") and biphenyl groups occurs by ring inversion through a planar D_{4h} structure (eq 2). It is interesting that the observed barrier to inversion corresponds closely to the calculated difference in energy between the D_{2d} and D_{4h} structures of hexadehydro[18]annulene (16.1 kcal mol^{-1}).[7b]

$$(2)$$
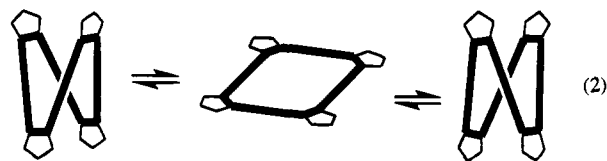
Reactions of **3** and **4** with concentrated HCl in THF afford the corresponding hydrolyzed macrocycles **5** and **6** in high yield (Scheme 1). Crystals of **5** from toluene/acetonitrile solution (−10 °C) contain 1.5 equiv of toluene and 1 equiv of acetonitrile per macrocycle, and the acetonitrile is located near the center of the macrocycle cavity, with its methyl carbon atom lying almost precisely in the least-squares plane of the macrocycle.[10] The ^{1}H and ^{13}C NMR spectra for **6** exhibit only one biphenyl environment (two resonances) over the temperature range −80

(10) Crystal data for **5**·NCMe·1.5PhMe: C$_{78.5}$H$_{99}$NSi$_6$, triclinic; $P\bar{1}$, $a = 11.847(3)$ Å, $b = 16.779(4)$ Å, $c = 20.128(4)$ Å, $\alpha = 83.64(2)°$, $\beta = 74.16(2)°$, $\gamma = 86.38(2)°$, $V = 3823(2)$ Å^3, $Z = 2$, $D_{calcd} = 1.06$ g cm^{-3}, μ(Mo Kα) = 1.4 cm^{-1}, $T = -80$ °C. The final residuals for 384 parameters refined against the 3580 accepted data ($F^2 > 3\sigma(F^2)$) were $R = 7.58\%$, $R_w = 8.24\%$, and GOF = 2.45.

to 40 °C. It therefore appears that **6**, unlike tetramer **4**, has D_{2d} symmetry. A less distorted (and more symmetric) geometry for **6** (vs **4**) is also supported by the fact that **5** and **6** have nearly identical UV−vis spectra, which contain transitions at 260 and 292 nm.

Generation of zirconocene in a different manner, by reduction of Cp$_2$ZrCl$_2$ with Mg, produces more of the kinetic product (7:3 ratio of **4** to **3**), but also higher oligomers (ca. 30% by weight), which have estimated degrees of polymerization from 5 to ca. 100 (by gel permeation chromatography; $M_w/M_n = 4400/1800$). These higher oligomers have not yet been separated from **3** and **4**, but it is assumed that they are cyclic compounds, on the basis of the absence of stretching vibrations for C≡CSiMe$_3$ groups in the IR spectrum. A hydrolyzed sample of the higher oligomers is yellow and possesses a UV−vis spectrum that is nearly identical to those for **5** and **6** (λ_{max} 260, 292 nm); however, much more tailing into the visible region (by ca. 50 nm, to 390 nm) is observed.

We are currently exploring numerous extensions of this diyne cyclization chemistry and will describe these shortly.