(CO$_{[N\text{-}t\text{-}BOC]}$), 138.7, 128.5, 127.7 (C-aryl$_{[BE]}$), 118.7 (CN), 80.5 (C(CH$_3$)$_{3[BA]}$), 78.9 (C(CH$_3$)$_{3[N\text{-}t\text{-}BOC]}$), 72.9 ($\mathit{C}H_2C_6H_{5[BE]}$), 28.7, 28.3 (C($\mathit{C}H_3$)$_{3[N\text{-}t\text{-}BOC,\ BA]}$), 18.9 ($\mathit{C}H_2CN_{[CN]}$). Similar signals are observed in the spectra of the homogeneous macromolecules **6**, **7**, **9**, and **10**. Higher generation materials can easily be constructed by further selective deprotection of functional groups and subsequent treatment with any mixture of compatible isocyanate-based monomers.

A great advantage of this protocol is the potential to adjust dendritic properties by modifying the surface groups. The polyamine dendrimer afforded by liberation of the NH$_2$ moieties on dendrimer **13** (50:50 mixture of *N*-*t*-BOC and BE terminal groups) displays amphiphilic behavior. For example, it is highly soluble in MeOH as well as partially soluble in both H$_2$O and CHCl$_3$; this compound is thus reminiscent of a "universal micelle". Key ^{13}C NMR signals arising from the NH$_2$- and PhCH$_2$O-terminated arms collapse and broaden in the deuterated solvents CDCl$_3$ and D$_2$O, respectively. This can be rationalized by considering that surface groups with termini that favor solvation are extended and freely rotating, while groups with unfavorable solvent interactions are contracted and folded back into the molecular superstructure where less freedom of movement is afforded. Fréchet et al.[16] observed analogous behavior when dendritic wedges were attached to polyethylene glycol star polymers. This behavior can be modified by altering the ratio of the functional groups on the dendrimer surface. For example, a dendrimer with a 75:25 mixture of amino and benzyl ether moieties is completely miscible in H$_2$O and insoluble in CHCl$_3$.

Combinatorial construction of dendrimers is well suited to the rapid design and construction of nanoscale superstructures having a variety of forms and functions. The large-scale screening of vastly differing material properties should thus be possible. These dendritic materials are likely to have cavities and clefts within the framework, resulting in various degrees of local as well as overall asymmetry. As such, these materials can be viewed as being intermediate between dendrimers and classical polymers: a "polycelle". We are currently investigating their potential use as catalysts and phase-transfer agents.

July 7, 1997 [Z10643IE]
German version: *Angew. Chem.* **1998**, *110*, 318–321

Keywords: combinatorial synthesis • dendrimers • isocyanates

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[1] G. R. Newkome, C. N. Moorefield, F. Vögtle, *Dendritic Molecules: Concepts, Syntheses, Perspectives*, VCH Weinheim, **1996**; C. N. Moorefield, G. R. Newkome, *Adv. Dendritic Macromol.* **1994**, *1*, 1; J. Issberner, R. Moors, F. Vögtle, *Angew. Chem.* **1994**, *106*, 2507; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 2413; J. M. J. Fréchet, C. J. Hawker, K. L. Wooley, *J. Macromol. Sci. Part A* **1994**, *31*, 1627; J. M. J. Fréchet, *Science* **1994**, *263*, 1710; D. A. Tomalia, A. M. Naylor, W. A. Goddard, III, *Angew. Chem.* **1990**, *102*, 119; *Angew. Chem. Int. Ed. Engl.* **1990**, *29*, 138; B. I. Voit, *Acta Polymer* **1995**, *46*, 87; N. Ardoin, D. Astruc, *Bull. Soc. Chim. Fr.* **1996**, *132*, 875.

[2] S. Stevelmans, J. C. M. van Hest, J. F. G. A. Jansen, D. A. F. J. van Boxtel, E. M. M. de Brabander-van den Berg, E. W. Meijer, *J. Am. Chem. Soc.* **1996**, *118*, 7398; G. R. Newkome, Z.-q. Yao, G. R. Baker, V. K. Gupta, *J. Org. Chem.* **1985**, *50*, 2003.

[3] G. R. Newkome, R. Güther, C. N. Moorefield, F. Cardullo, L. Echegoyen, E. Pérez-Cordero, H. Luftmann, *Angew. Chem.* **1995**, *107*, 2159; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2023.

[4] S. A. Kuzdzal, C. A. Monnig, G. R. Newkome, C. N. Moorefield, *J. Chem. Soc. Chem. Commun.* **1994**, 2139; *J. Am. Chem. Soc.* **1997**, *119*, 2255.

[5] G. R. Newkome, C. N. Moorefield, J. M. Keith, G. R. Baker, G. H. Escamilla, *Angew. Chem.* **1994**, *106*, 701; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 666; R. F. Barth, A. H. Soloway, *Mol. Chem. Neuropathol.* **1994**, *21*, 139; R. F. Barth, D. M. Adams, A. H. Soloway, F. Alam, M. V. Darby, *Bioconjugate Chem.* **1994**, *5*, 58.

[6] R. J. Duan, L. L. Miller, D. A. Tomalia, *J. Am. Chem. Soc.* **1995**, *117*, 10783.

[7] G. R. Newkome, C. D. Weis, C. N. Moorefield, F. R. Fronczek, *Tetrahedron Lett.* **1997**, *38*, 7053; G. R. Newkome, C. D. Weis, U.S. Patent 5703271 (December 30, 1997).

[8] G. R. Newkome, C. D. Weis, B. J. Childs, *Designed Monomers Polym.* **1997**, in press

[9] X.-D. Xiang, X. Sun, G. Briceño, Y. Lou, K.-A. Wang, H. Chang, W. G. Wallace-Freedman, S.-W. Chen, P. G. Schultz, *Science* **1995**, *268*, 1783.

[10] T. Carell, E. A. Wintner, A. J. Sutherland, J. Rebek, Jr., Y. M. Dunayevskiy, P. Vouros, *Chem. Biol.* **1995**, *2*, 171; L. Bourel, X. Willard, I. Pop, R. Bandelle, D. Horvath, B. Déprey, P. Melnyk, A. Tartar, *L'Actual. Chem.* **1995**(12), 33; M. Cardno, M. Bradley, *Tetrahedron Lett.* **1996**, *37*, 135.

[11] M. Goodman, V. Jubian, B. Linton, A. D. Hamilton, *J. Am. Chem. Soc.* **1995**, *117*, 11610.

[12] R. M. Kim, M. Manna, S. M. Hutchins, P. R. Griffin, N. A. Yates, A. M. Bernick, K. T. Chapman, *Proc. Natl. Acad. Sci. USA* **1996**, *93*, 10012.

[13] V. Swali, N. J. Wells, G. J. Langley, M. Bradley, *J. Org. Chem.* **1997**, *62*, 4902.

[14] D. Seebach, R. E. Marti, T. Hintermann, *Helv. Chim. Acta* **1996**, *79*, 1710.

[15] Commercially available poly(propylene imine) dendrimers were generously provided by DSM. The preparation and characterization was reported: E. M. M. de Brabander-van den Berg, E. W. Meijer, *Angew. Chem.* **1993**, *105*, 1370; *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1308; C. Wörner, R. Mülhaupt, *Angew. Chem.* **1993**, *105*, 1367; *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1306.

[16] I. Gitsov, J. M. J. Fréchet, *J. Am. Chem. Soc.* **1996**, *118*, 3785; *Macromolecules* **1993**, *26*, 6536.

Self-Assembly of Novel Polyrotaxanes: Main-Chain Pseudopolyrotaxanes with Poly(ester crown ether) Backbones**

Caiguo Gong and Harry W. Gibson*

Physically linked molecules, rotaxanes and catenanes,[1] comprise a major research field of supramolecular chemistry[2] which has fascinated scientists in recent decades. Polyrotaxanes, in which a cyclic and a linear species (one of which is part of a macromolecule) are mechanically interlocked with each other, have also been extensively studied since their properties are different than those of conventional covalent polymers.[1, 3–10] The novel properties of these compounds often result from their unusual architectures. Therefore, designing

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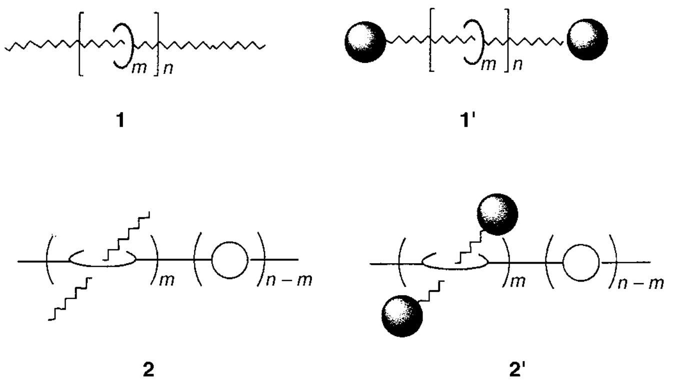
[**] This work was supported by the National Science Foundation through Individual Investigator Awards DMR-93-20196 and DMR-97-06909.

and synthesizing polyrotaxanes with new topologies is very important to polymer science. Two types of main-chain polyrotaxanes are proposed:[1a, 1d] types **1** and **1′** as well as types **2** and **2′** (Scheme 1). To our knowledge, however, only main-chain polyrotaxanes of types **1** and **1′** have been constructed by threading macrocycles onto polymeric backbones.[1, 3, 5–10] Here, we report an approach to polyrotaxanes of type **2** which self-assemble by threading linear components of low molar mass through the cavities of in-chain cyclic units of a preformed poly(ester crown ether).

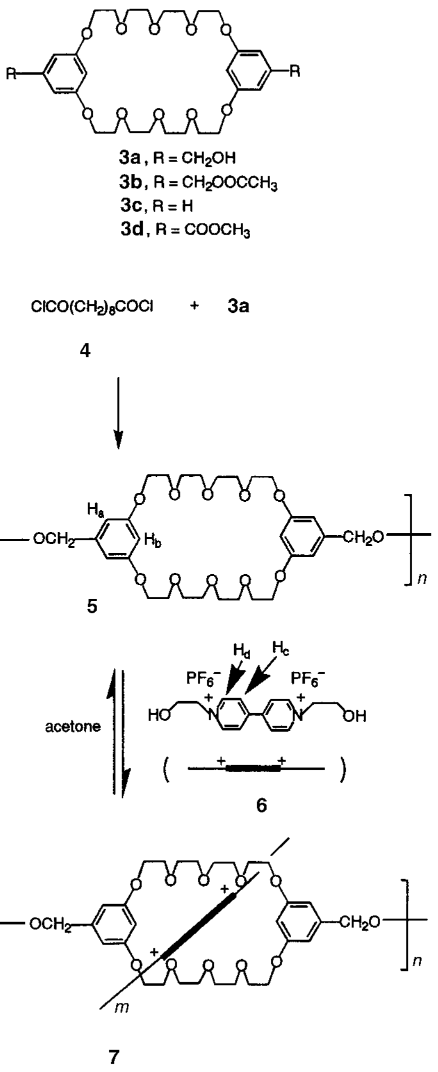


Scheme 1. Different types of main-chain polyrotaxanes: main-chain pseudopolyrotaxanes (**1**, **2**) and main-chain polyrotaxanes (**1′**, **2′**).

The difunctional macrocycles bis(5-hydroxymethyl-*m*-phenylene)-[32]crown-10 (**3a**), bis(5-acetoxymethyl-*m*-phenylene)-[32]crown-10 (**3b**), and bis(*m*-phenylene)-[32]crown-10 (BMP32C10) derivatives **3c** and **3d** were prepared by a well-established procedure.[11] Polycondensation of **3a** with sebacoyl chloride (**4**) afforded poly(sebacate crown ether) **5** (see Scheme 2), which can serve as a backbone for constructing designed main-chain polyrotaxanes.

Stoddart et al. demonstrated that bis-phenylene-based crown ethers complex with bipyridinium salts under charge transfer accompanied by hydrogen bonding and dipole–dipole interactions.[1, 12] More specifically, they found that **3c** and *N,N′*-dimethyl-4,4′-bipyridinium hexafluorophosphate ("paraquat") formed a pseudorotaxane.[12a] Therefore, *N,N′*-bis(*β*-hydroxyethyl)-4,4′-bipyridinium hexafluorophosphate (**6**)[13] is expected to penetrate the cavity of the cyclic component of **5** to form the targeted main-chain pseudopolyrotaxane **7** (Scheme 2).

Indeed, a solution of **6** in acetone immediately turned orange upon addition of **5**, indicating the formation of **7**.[1, 8, 9, 12] ^{1}H NMR spectroscopy affords direct evidence. The signals for the aromatic protons H_a and H_b of the macrocyclic moiety in **7** (Figure 1 b, c) shifted upfield upon complexation with respect to those for **5** (Figure 1 a); this is consistent with the expected complexation, that is, the existence of through-space interactions owing to π stacking between these two components.[1, 8, 9, 12] All these signals are time-averaged; no peaks corresponding to threaded and unthreaded structures exist in the room-temperature spectra. Therefore, although the cyclic component was incorporated into the backbone, the complexation is still rapid on the ^{1}H NMR time scale.



Scheme 2. Preparation of poly(sebacate crown ether) **5** and polyrotaxane **7**.

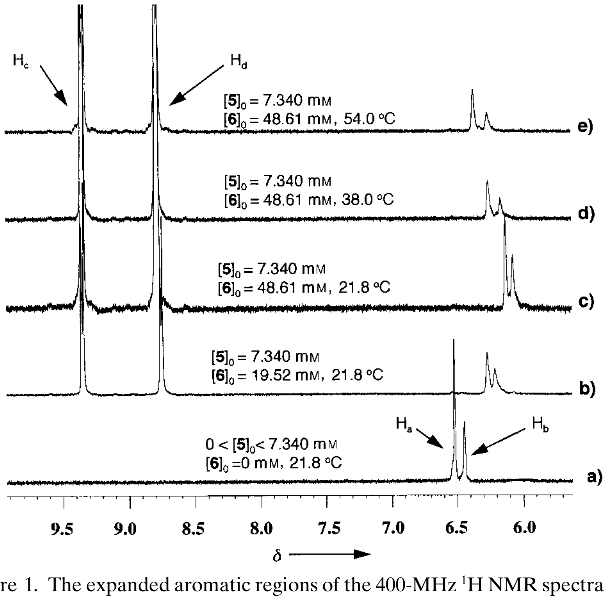


Figure 1. The expanded aromatic regions of the 400-MHz ^{1}H NMR spectra of a) **5** and b–e) solutions of **5**, **6**, and **7** of different compositions and at different temperatures in [D$_6$]acetone.

Since the complexation is rapid, the chemical shifts for the totally complexed form (e.g. H_a or H_b of the cyclic moiety in **7**) are necessary to calculate the equilibrium constant K.[2a] The continuous titration of a solution of **5** with **6** according to Benesi–Hildebrand method[14] gave the corresponding Δ values for proton H_b (Table 1). The plot of $1/\Delta$ versus $1/[\mathbf{6}]_0$ (Figure 2) afforded K and Δ_0, which are $39.6\,\text{M}^{-1}$ and 0.556 ppm, respectively, for the formation of **7** in acetone at 21.8 °C (Table 2). For any other given stoichiometry the percentage of threaded macrocycle, that is, the threading efficiency [m/n value; fraction of cyclic repeat units threaded = [**7**]/([**5**] + [**7**])] can be derived (Table 1).

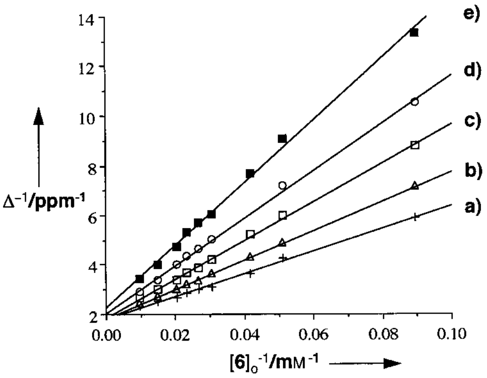


Figure 2. Benesi–Hildebrand plots for the formation of polyrotaxane **7** at a) 21.8, b) 30.0, c) 38.0, d) 46.0, and e) 54.0 °C in acetone.

Table 1. The feed concentrations of **5** and **6**, the changes in chemical shift, and the threading effienencies of **7** in [D$_6$]acetone at 21.8 °C.

$[\mathbf{5}]_0$[a] [mM]	$[\mathbf{6}]_0$ [mM]	δ_0/Δ[b]	m/n for **7**[c]
0–7.340[d]	0	6.441/0.000	0
7.340	11.16	6.271/0.170	0.306
7.340	19.52	6.206/0.235	0.425
7.340	23.87	6.166/0.275	0.495
7.340	32.54	6.119/0.322	0.582
7.340	37.43	6.111/0.330	0.597
7.340	42.55	6.094/0.347	0.628
7.340	48.61	6.070/0.371	0.671
7.340	67.00	6.042/0.399	0.722
7.340	100.8	6.010/0.431	0.779

[a] Based on the cyclic units. [b] Based on the chemical shift of H_b (measured with ^{1}H NMR spectroscopy[14]). [c] Calculated according to ref. [14]. [d] Polymer **5** by itself is only partially soluble in acetone.

Because the complexation is exothermic, increasing the temperature disfavors rotaxane formation. This is indicated by the fact that the signals for H_a and H_b are shifted downfield at higher temperatures (Figure 1c–e). To quantitively understand the effect of temperature on the complexation, K values were measured at different temperatures according to the above-mentioned method (Figure 2b–e and Table 2); K indeed decreases with increasing temperature. From the van't Hoff plot (Figure 3a) ΔH was determined to be $-1.93\times10^4\,\text{J}\,\text{mol}^{-1}$, and ΔS $-35.0\,\text{J}\,\text{K}^{-1}\text{mol}^{-1}$. Therefore, as shown in Figure 4, the threading efficiency m/n of polyrotaxane **7** can be controlled by simply varying the temperature and the concentration; that is, the m/n values for **7** increase for higher ratios of **6** to **5** at a given temperature as well as for a given concentration at lower temperatures.

Table 2. Equilibrium constants and changes in free energy for the complexation of **5** and **6** at different temperatures in [D$_6$]acetone.

T [K][a]	Slope[b] [mM ppm^{-1}]	Intercept[b] [ppm^{-1}]	R^2[b]	Δ_0[b] [ppm]	K[b] [M^{-1}]	ΔG [kJ mol^{-1}]
295.0	45.6	1.80	0.996	0.556	39.6	−9.02
303.2	59.3	1.83	1.000	0.547	30.9	−8.65
311.2	78.0	1.87	0.998	0.535	23.9	−8.21
319.2	95.8	2.07	0.998	0.484	21.6	−8.15
327.2	126	2.28	0.996	0.439	18.0	−7.88

[a] ±0.1 K. [b] Based on the Benesi–Hildebrand plot (Figure 2).

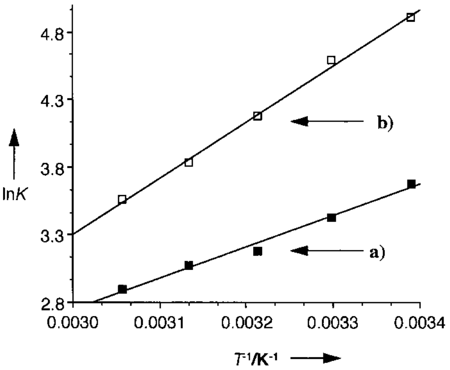


Figure 3. van't Hoff plots for a) the polymer system **5** + **6** and b) the model system **3b** + **6**. Curve a): intercept: −4.21; slope: 2.32×10^3 (K); $R^2 = 0.985$. Curve b): intercept: −9.17; slope: 4.16×10^3 (K); $R^2 = 0.997$.

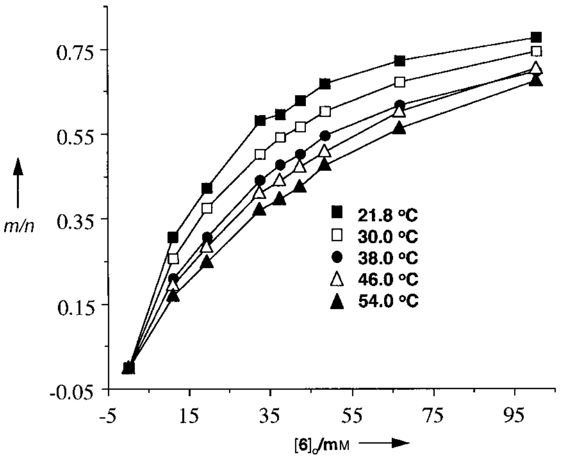


Figure 4. The relationship between the threading efficiency (m/n) of **7** and the feed concentration of **6** with $[\mathbf{5}]_0 = 7.340$ mM in [D$_6$]acetone at different temperatures.

The K value at room temperature for the polymeric system is much lower than that reported for the complexation of monomeric **3c** with **6** ($760\,\text{M}^{-1}$, room temperature).[12a] To take into account the possible effect of the ester linkage in **5**, a model study was carried out with the diester derivative **3b** and **6**. The K value obtained ($135\,\mathrm{M}^{-1}$ at 21.8 °C)[16] is also higher than that for the polymeric system ($39.6\,\mathrm{M}^{-1}$ at 21.8 °C, Table 1). We believe that is the difference is due to the reduced flexibility of the cyclic units in **5**. For π stacking to occur, the phenylene rings of the macrocycle have to rotate towards each other relative to their parallel but nonoverlapping comformation in the uncomplexed state.[12a, 17] As soon as they are incorporated into the polymer backbone, rotation of these phenyl rings becomes much more difficult because it involves local or probably more extensive chain movement; this leads to enthalpic penalties and consequently a lower K value. Indeed, ΔH is more negative for the model system ($-3.46\times10^{4}\,\mathrm{J\,mol^{-1}}$, Figure 3b). On the other hand, the ethyleneoxy units of the cyclic moiety in polymer **5** are restricted and expected to be less flexible than in the free macrocycle **3b**, whereas both will be rigidified upon complexation with **6**; this results in a more negative ΔS for the model system ($-76.2\,\mathrm{J\,K^{-1}mol^{-1}}$)[16] than for polymeric **7**.

Because of its new topology polyrotaxane **7** had different physical properties than the starting polymer **5**. Polymer **5** is only partially soluble in acetone (Table 1), and paraquat **6** is insoluble in THF. Pseudopolyrotaxanes **7**, however, are soluble in both acetone and THF. Furthermore, the reduced viscosity of **7** prepared with reagent concentrations of $[\mathbf{5}]_0 = 7.427\,\mathrm{mM}$ and $[\mathbf{6}]_0 = 22.28\,\mathrm{mM}$ ($m/n = 0.430$[18]) is $0.215\,\mathrm{dL\,g^{-1}}$, which is much higher than the value of $0.122\,\mathrm{dL\,g^{-1}}$ for **7** prepared with $[\mathbf{5}]_0 = 7.427\,\mathrm{mM}$ and $[\mathbf{6}]_0 = 1.857\,\mathrm{mM}$ ($m/n = 0.0544$[18]) in acetone at 21.8 °C. The higher viscosity indicates a larger hydrodynamic volume for the pseudopolyrotaxane **7** with higher m/n.

Polymer **5** is a colorless elastomer with a glass-transition temperature T_g of -6.3 °C. Interestingly, **7** ($m/n = 0.69$)[19] obtained by freeze-drying a solution of **5** and **6** (molar ratio 1:0.75) is a glassy orange material with a T_g of 85.6 °C; the higher for **7** is attributed to its increased rigidity after complexation. The orange color proved that the rotaxane structure **7** in solution remained in the solid state after freeze-drying. This is very important, because use of these pseudopolyrotaxanes in the solid state becomes possible.

We have demonstrated an approach to novel main-chain polyrotaxanes of type **2** (Scheme 1) for the construction of pseudopolyrotaxane **7** by threading linear species **6** through the cavities of the cyclic repeat units of polymacrocycle **5**. Polyrotaxane **7** has a higher viscosity and higher T_g than its starting backbone **5**, and shows different solubility characteristics. The m/n value for the solution of the polyrotaxane increases with increasing amounts of bipyridinium salt **6** as well as with decreasing temperature. The values of K, ΔH, and ΔS provide the basis for predicting the threading efficiency for the preparation of analogous polyrotaxanes. Since bipyridinium guest **6** bears two hydroxy groups, **7** can further react, for example, with diisocyanates to form interesting networks. We are currently studying such systems.

Experimental Section

6: Macrocycle **3a** (150.0 mg, 0.6272 mmol) and **4** (374.3 mg, 0.6272 mmol) were dissolved in a mixture of diglyme and dimethyl sulfoxide (DMSO; 4 mL, 1/1 v/v) at 60 °C. Polymerization proceeded for 2 d at this temperature under N_2. The product was purified by precipitation into methanol (100 mL) to afford **6** (421.1 mg, 88 %), $M_n = 14.9\,\mathrm{kg\,mol^{-1}}$, PDI = 1.97 (gel permeation chromatography with polystyrene standards).

Received: July 15, 1997
Revised version: October 21, 1997 [Z 10685 IE]
German version: *Angew. Chem.* **1998**, *110*, 323 – 327

Keywords: crown compounds · host – guest chemistry · polymers · rotaxanes · supramolecular chemistry

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[1] Reviews: a) H. W. Gibson, M. C. Bheda, P. T. Engen, *Prog. Polym. Sci.* **1994**, *19*, 843 – 945; b) D. B. Amabilino, J. F. Stoddart, *Chem. Rev.* **1995**, *95*, 2725 – 2828; c) D. Philp, J. F. Stoddart, *Angew. Chem.* **1996**, *108*, 1242 – 1286; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1154 – 1196; d) H. W. Gibson in *Large Ring Molecules* (Ed.: J. A. Semlyen), Wiley, New York, **1996**, pp. 191 – 262.

[2] Reviews: a) *Comprehensive Supramolecular Chemistry, Vol. 6* (Eds.: J. L. Atwood, J. E. D. Davies, D. D. MacNicol, F. Vögtle), Pergamon, Oxford, **1996**; b) J.-M. Lehn, *Supramolecular Chemistry*, VCH, New York, **1995**; c) D. J. Cram, J. M. Cram, *Container Molecules and Their Guests*, Royal Society of Chemistry, Cambridge, **1994**; d) F. Vögtle, *Supramolecular Chemistry*, Wiley, New York, **1991**.

[3] M. B. Steinbrunn, G. Wenz, *Angew. Chem.* **1996**, *108*, 2274 – 2277; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 2139 – 2142; W. Herrmann, B. Keller, G. Wenz, *Macromolecules*, **1997**, *30*, 4966 – 4972.

[4] a) M. Born, H. Ritter, *Adv. Mater.* **1996**, *8*, 149 – 151; b) M. Born, H. Ritter, *Macromol. Rapid Commun.* **1996**, *17*, 197 – 202; c) O. Noll, H. Ritter, *ibid.*, **1997**, *18*, 53 – 58.

[5] a) A. Harada, J. Li, M. Kamachi, *Macromolecules* **1994**, *27*, 4538 – 4543; b) A. Harada, M. Okada, J. Li, M. Kamachi, *ibid.* **1995**, *28*, 8406 – 8411; c) A. Harada, J. Li, M. Kamachi, *Chem. Commun.* **1997**, 1413 – 1414.

[6] Y. X. Shen, D. Xie, H. W. Gibson, *J. Am. Chem. Soc.* **1994**, *116*, 537 – 548; H. W. Gibson, S. Liu, P. Lecavalier, C. Wu, Y. X. Shen, *ibid.* **1995**, *117*, 852 – 874; H. W. Gibson, S. Liu, C. Gong, Q. Ji, E. Joseph, *Macromolecules*, **1997**, *30*, 3711 – 3727.

[7] C. Gong, H. W. Gibson, *Macromolecules* **1996**, *29*, 7029 – 7033; C. Gong, H. W. Gibson, *Macromol. Chem. Phys.* **1997**, *198*, 2321 – 2332; C. Gong, Q. Ji, T. E. Glass, H. W. Gibson, *Macromolecules* **1997**, *30*, 4807 – 4813.

[8] H. W. Gibson, S. Liu, Y. X. Shen, M. C. Bheda, S.-H. Lee, F. Wang, *NATO ASI Ser. Ser. C* **1995**, *456*, 41 – 58.

[9] P. E. Mason, I. W. Parsons, M. S. Tolley, *Angew. Chem.* **1996**, *108*, 2405 – 2408; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 2238 – 2241; G. J. Owen, P. Hodge, *Chem. Commun.* **1997**, 11 – 12.

[10] a) C. Gong, H. W. Gibson, *J. Am. Chem. Soc.* **1996**, *119*, 5862 – 5866; b) *ibid.* **1996**, *119*, 8585 – 8591.

[11] H. W. Gibson, D. S. Nagvekar, *Can. J. Chem.* **1997**, *75*, 1375 – 1384.

[12] a) B. L. Allwood, N. Spencer, H. Shahriari-Zavareh, J. F. Stoddart, D. J. Williams, *J. Chem. Soc. Chem. Commun.* **1987**, 1058 – 1061; b) M. Asakawa, P. R. Ashton, R. Ballardini, V. Balzani, M. Belohradsky, M. T. Gandolfi, O. Kocian, L. Prodi, F. M. Raymo, J. F. Stoddart, M. Venturi, *J. Am. Chem. Soc.* **1997**, *119*, 302 – 310, and references therein.

[13] Y. X. Shen, P. T. Engen, M. A. G. Berg, J. S. Merola, H. W. Gibson, *Macromolecules* **1992**, *25*, 2786 – 2788.

[14] The association constant K is calculated according to the Benesi – Hildebrand method[15] as follows: For a given temperature and a given feed concentration of one component (e.g. $[\mathbf{5}]_0$), the feed concentration of another component (e.g. $[\mathbf{6}]_0$) is changed: $1/\Delta = 1/(\Delta_0 K[\mathbf{6}]_0) + 1/\Delta_0$, where $\Delta = \delta_f - \delta$, $\Delta_0 = \delta_f - \delta_c$, and δ, δ_c, and δ_f are the time-averaged chemical shifts of the partially complexed, totally complexed, and unthreaded forms, respectively (e.g. H_a and H_b of **5**). Therefore, K, Δ_0, and m/n (threading effiency = Δ/Δ_0) were calculated (Table 2) from the plot of $1/\Delta$ vs. $1/[\mathbf{6}]_0$ (Figure 2).

[15] H. A. Benesi, J. H. Hildebrand, *J. Am. Chem. Soc.* **1949**, *71*, 2703 – 2710; H. Tsukube, H. Furuta, A. Odani, Y. Takeda, Y. Kudo, Y. Inone, Y. Liu, H. Sakamoto, K. Kimura, *Comprehensive Supramolecular*

Chemistry, Vol. 6 (Eds.: J. L. Atwood, J. E. D. Davies, D. D. MacNicol, F. Vögtle), Pergamon, Oxford, **1996**, pp. 425–482.

[16] The values for K, ΔH, and ΔS were also determined by the Benesi–Hildebrand method.[14, 15] K values in [D$_6$]acetone: 135 M^{-1} at 21.8 °C, 98.1 M^{-1} at 30.0 °C, 65.6 M^{-1} at 38.0 °C, 46.1 M^{-1} at 46.0 °C, 34.9 M^{-1} at 54.0 °C; $\Delta H = -34.6 \times 10^4$ J mol^{-1}; $\Delta S = -76.2$ J K^{-1} mol^{-1} (Figure 3 b).

[17] The crystal structure of **3c** indicates an open cavity (4.9 × 7.8 Å) which undergoes a small conformational change when it complexes with paraquat.[12a] However, **3d** in the solid state has a collapsed cavity (0.75 × 7.8 Å), perhaps due to crystal packing forces and not intrinsic conformational preferences: Y. Delaviz, J. S. Merola, M. A. G. Berg, H. W. Gibson, *J. Org. Chem.* **1995**, *60*, 516–522.

[18] The values for m/n were calculated by the method specified in ref. [14].

[19] The solution of **5** and **6** in acetone was slowly cooled to −90 °C and then frozen with an acetone/dry ice bath. The solvent was removed under high vacuum to afford an orange solid, pseudopolyrotaxane **7**. The m/n value was calculated from K (4748 M^{-1}), which was estimated from the measured ΔH and ΔS values.

The Use of ^{15}N NMR Spectroscopy To Resolve the "Higher Order Cyanocuprate" Controversy: ^{15}N, ^{6}Li, and ^{13}C NMR Spectroscopic Investigations of CuCN-Derived Butyl Cuprates**

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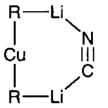
In the modern era of organocopper chemistry,[1] the first cyanocuprate experiments involved the addition of one equivalent of RLi to CuCN to prepare cyanocuprates RCu(CN)Li.[2] Two-bond ^{13}C-^{13}C coupling constants ^2J across copper proved that the R group and the CN group are both bonded to the same Cu in these 1:1 reagents.[3] In 1981 Lipshutz et al. added two equivalents of RLi to CuCN and claimed not only a new class of highly reactive reagents but a new *kind* of organocopper(I) species, the "higher order cyanocuprates."[4] Spectroscopic evidence was not presented, but NMR and IR data were reported later.[5]

Subsequently, Bertz showed that the ^{13}C NMR chemical shifts of the cuprates prepared from two equivalents of RLi and CuCN or CuI were the same and that the shift of the CN carbon atom was independent of the electronic nature of R.[6] In contrast, the chemical shifts of the CN carbon atoms in the "lower order" cyanocuprates RCu(CN)Li vary with R.[3, 6] These observations and the absence of ^2J in the 2:1 compounds cast grave doubt on the higher order formulation R$_2$Cu(CN)Li$_2$.[4, 7] Extended X-ray absorption fine structure (EXAFS)[8, 9] investigations by Penner-Hahn, Knochel, Frenking et al. and IR[10] studies by Penner-Hahn, Snyder et al. supported the conclusions of these NMR studies. Theoretical investigations by Snyder et al.[11] and Penner-Hahn, Knochel, Frenking et al.[9] indicated that higher order structures are 20–30 kcal mol^{-1} higher in energy than lower order alternatives.

Various lower order structures have been proposed for the 2:1 reagents, for example, **1**–**3**. They are related to the Gilman dimer **4** by the substitution of CN$^-$ for R$_2$Cu$^-$ in three archetypal ways : 1) one Li atom is attached to N and one to C, 2) both Li atoms are bonded to N, and 3) both Li atoms are bonded to C. While initial theoretical studies favored variants of **1**–**3**,[11] all of these cyano-Gilman reagents are close enough in energy to be viable candidates. We have now prepared the 1:1 and 2:1 reagents, BuCu(C^{15}N)^{6}Li and Bu$_2$Cu^{6}Li · ^{6}LiC^{15}N, respectively, as well as intermediate stoichiometries from Bu^{6}Li and CuC^{15}N.[12] The results of this ^{15}N NMR study, coupled with theoretical calculations reported herein, strongly support structure **1** over the others.



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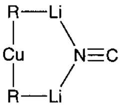

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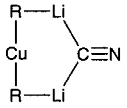

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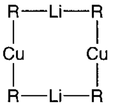

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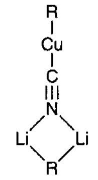

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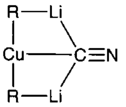

6

Figure 1 shows the ^{15}N NMR spectra of solutions in [D$_8$]THF at −80 °C when a) 1.0, b) 1.3, or c) 2.0 equivalents of Bu^{6}Li is added to CuC^{15}N.[12] The 1:1 reagent BuCu(C^{15}N)-^{6}Li is characterized by a singlet at $\delta = -129.3$ (6 Hz width at

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[**] New Copper Chemistry, Part 28. The authors are grateful to Lars Baltzer and Thomas Andersson for technical assistance and to the Swedish Natural Science Research Council for partial support of this work. S.H.B. wishes to thank Christina Ullenius for arranging this collaboration and Mikael Håkansson for helpful discussions. J.P.S. wishes to thank Dennis Liotta for his hospitality. Part 27: S. H. Bertz, M. Eriksson, G. Miao, J. P. Snyder, *J. Am. Chem. Soc.* **1996**, *118*, 10906–10907.