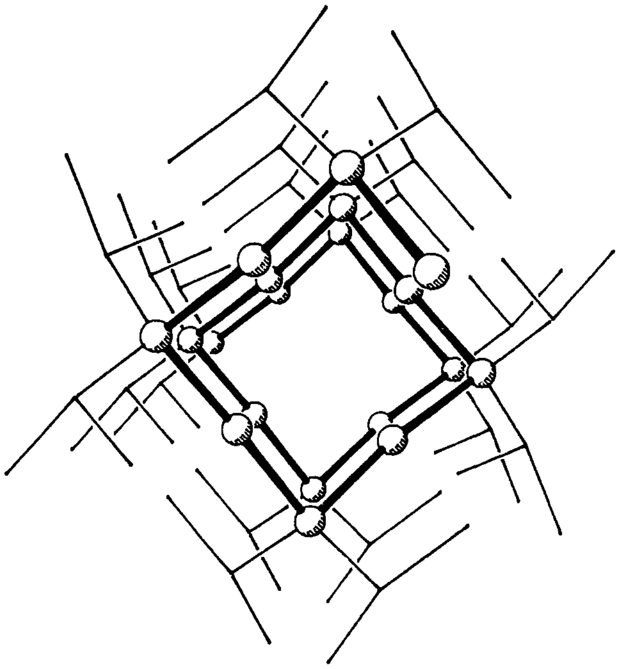

Figure 1. An axial view of the helix structure of crystalline LDA. Hydrogen atoms have been omitted for clarity.

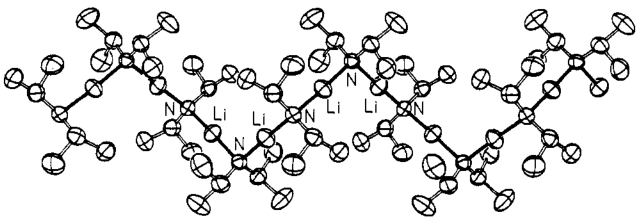

Figure 2. A side view of the same section of the helix showing thermal ellipsoids (at the 50% probability level). A representative sample of N and Li atoms are labeled.

Table I. Selected Bond Lengths (Å) and Angles (deg)

Li(1)-N(1)	1.957 (5)	N(1)-Li(1)-N(2′)	177.9 (3)
Li(1)-N(2′)	1.934 (5)	N(1)-Li(2)-N(2)	174.1 (2)
Li(2)-N(2)	1.956 (4)	Li(1)-N(1)-Li(2)	108.3 (2)
Li(2)-N(1)	1.939 (4)	Li(1′)-N(2)-Li(2)	109.5 (2)

a crop of almost colorless (with slight brown tinge) crystals.[8] Removing the mother liquor, washing with hexane aliquots, and evacuating to dryness has no adverse effect on their crystallinity, and although sensitive to atmospheric moisture and oxygen they are nonpyrophoric. Traces of diisopropylamine and, less significantly, of TMEDA in the crystalline composition can be detected by ^{1}H NMR spectroscopic analysis.[9] Based on integration ratios, a typical empirical formula is $[(\mathrm{Pr^i{}_2NLi})(\mathrm{Pr^i{}_2NH})_{1/10}(\mathrm{TMEDA})_{1/40}]$.

Pure LDA is a fine powdery white solid, so its crystalline state here must be promoted by the small quantities of $\mathrm{Pr^i{}_2NH}$/TMEDA present. However, these potential donor ligands do not show up in the electron density map obtained by the X-ray diffraction study. They form no part of the regular crystalline structure; possibly they play a role in polymer chain termination at the crystal surface and at defect sites in the structure.

LDA adopts an eye-catching helical arrangement (Figure 1) in the crystal phase.[10] An alternative view looking through a section of the helix shell, rather than through its central cavity, is shown in Figure 2. Table I lists selected bond lengths and bond angles. Each two-coordinate $\mathrm{Li^+}$ center engages in one short bond (average length, 1.937 Å) and one slightly longer bond (average length, 1.957 Å) to essentially tetrahedral, four-coordinate $\mathrm{N^-}$ centers. The polymer is thus composed of unsymmetrical N-Li-N units, approximately linear in shape (average N-Li-N bond angle, 176°). These triatomic units link up so that the short and long N-Li bonds alternate throughout the coiled structure. A turn of the helix consists of four such units (eight N-Li bonds in total). The repeat distance between turns (i.e., between like atoms that are eclipsed along the axis of the helix) is 9.567 Å. Finally, it should be pointed out that the centrosymmetric crystal structure contains equal numbers of right-handed and left-handed helices. Figure 1 depicts the latter type.

Acknowledgment. We thank the Associated Octel Co. Ltd. (N.D.R.B. and R.E.M.) for sponsoring this research and their representatives Dr. J. Barker and Dr. D. Barr for many helpful discussions; the Royal Society (R.E.M. and W.C.) and the SERC (W.C. and P.A.O.) for providing additional financial support; and Dr. P. R. Dennison of Strathclyde University for running the NMR spectrum.

Registry No. LDA, 4111-54-0; TMEDA, 110-18-9.

Supplementary Material Available: Details of the X-ray analysis of LDA and tables of atomic coordinates, bond lengths and angles, and thermal parameters for LDA (5 pages); listing of observed and calculated structure factors for LDA (11 pages). Ordering information is given on any current masthead page.

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[8] Yield of first batch obtained after 24 h of refrigerator cooling, 59% (based on consumption of freshly standardized $\mathrm{Bu^tLi}$). Attempts to optimize the yield are in progress. This crystalline form of LDA is the subject of a preliminary patent filed by the Associated Octel Co. Ltd., Ellesmere Port, U.K.

[9] ^{1}H NMR spectrum (recorded at 400 MHz in tetrahydrofuran-d_8 solution; 263 K): $\mathrm{Pr^i}$(C*H*), 1 H, sep, δ 2.99 ppm; $\mathrm{Pr^i}$(C*H*)-amine, ≪1 H, oct, δ 2.85 ppm; $\mathrm{C}H_2$-TMEDA, ≪1 H, s, δ 2.29 ppm; $\mathrm{C}H_3$-TMEDA, ≪1 H, s, δ 2.14 ppm; $\mathrm{Pr^i}(\mathrm{C}H_3)$, 6 H, d, δ 0.97 ppm; $\mathrm{Pr^i}(\mathrm{C}H_3)$-amine, <1 H, d, δ 0.94 ppm. Relative to TMS, δ 0.00 ppm. A comparison with a solution of $\mathrm{Pr^i{}_2NH}$ and TMEDA in the same solvent indicates that both ligands are "free" here and not attached to the $\mathrm{Li^+}$ cations. In this medium the $\mathrm{Li^+}$ centers will be complexed by tetrahydrofuran molecules (see ref 3 for details).

[10] Crystal data: $\mathrm{C_6H_{14}NLi}$, $M = 107.1$, monoclinic, $P2_1/n$, $a = 9.146$ (3) Å, $b = 9.567$ (3) Å, $c = 17.740$ (7) Å, $\beta = 92.91$ (3)°, $V = 1550.4$ Å^3, $Z = 8$, $D_{\mathrm{calcd}} = 0.918$ g cm^{-3}, $\lambda(\mathrm{Cu}\ K\alpha) = 1.54184$ Å, $\mu = 0.354$ mm^{-1}, $F(000) = 480$. Measurements were made at 240 K on a Stoe-Siemens diffractometer with an Oxford Cryostream cooler from a crystal of size 0.50 × 0.58 × 0.61 mm; 1880 unique observed reflections were used for structure determination by direct methods and least-squares refinement on F, with weighting $w = 1/\sigma^2(F)$. H atoms were constrained, and other atoms were assigned anisotropic thermal parameters. At convergence, $R = 0.0562$, $R' = 0.0673$, goodness of fit = 1.01 for 170 parameters. All features in a final difference synthesis were within ±0.18 e Å^{-3}. Program system: SHELXTL (G. M. Sheldrick, University of Göttingen, Germany).

Novel Class of Asymmetric Zwitterionic Rotaxanes Based on α-Cyclodextrin

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Rotaxanes[1] are molecules in which a cyclic structure is threaded by a chain or other linear subunit having bulky ends that prevent the dissociation (or unthreading) of the cyclic and linear components. We report here the synthesis of a new class of rotaxanes based on the inclusion of alkyl chains by α-cyclodextrin (α-CD). The CD is locked onto the alkyl chain by two different bulky groups covalently attached to the ends of the chain. Two isomeric rotaxanes are formed which differ by the orientation of the CD torus with respect to the terminal groups.

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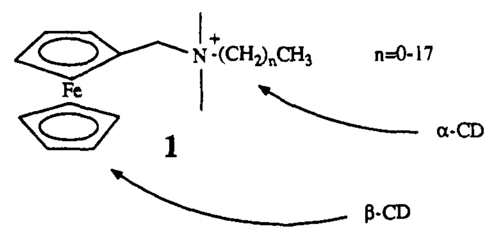
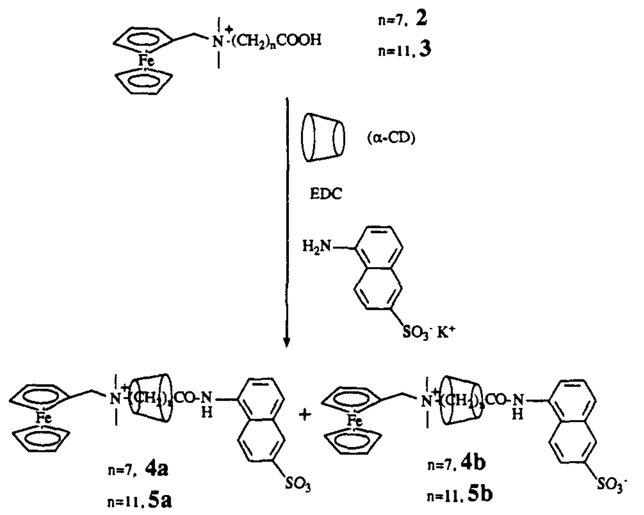
[1] Schill, G. *Catenanes, Rotaxanes, and Knots*; Academic Press: New York, 1971.

Scheme I



Scheme II



A few examples of symmetric rotaxanes based on CDs have been reported.[2,3] Quite recently, Lawrence and co-workers described the self-assembly of a threaded molecular loop which can be considered as a CD-based rotaxane in which the capping groups are held in place by ionic forces.[4] Our own synthetic design is based on our study of the interactions between alkyldimethyl(ferrocenylmethyl)ammonium cations (**1**) and unmodified CDs.[5] We have demonstrated that cations **1** exhibit bimodal complexation by CDs. Specifically, β-CD interacts preferentially with the ferrocene subunit while α-CD binds selectively to the alkyl chain (see Scheme I). Since the dimethyl(ferrocenylmethyl)ammonium unit in compound **1** closes the alkyl chain at one end, we reasoned that it would be possible to trap the chain-threaded α-CD if an appropriately reactive group were positioned at the other end of the chain. With this idea, we synthesized compounds **2** and **3** (see Scheme II) in which a carboxylic acid group is attached at the end of the chain. In these compounds the COOH group acts as an ionizable gate to the chain, i.e., deprotonation results in a 6-fold decrease of the binding constant with α-CD.[6] Once the cyclodextrin is bound, the presence of the terminal carboxylic acid group can be utilized to cap the rotaxane via standard amidation procedures. For instance, treatment of **2** with 2 equiv of α-CD, 1 equiv of 1-(3-[dimethylamino)propyl]-3-ethylcarbodiimide hydrochloride (EDC) as a catalyst, and 1 equiv of potassium 5-amino-2-naphthalenesulfonate in water produces a mixture of the isomeric rotaxanes **4a** and **4b** in 15% isolated yield. The CD-free compound **6**, resulting from the direct coupling of uncomplexed **2** and 5-amino-2-naphthalenesulfonate, was also isolated from the reaction mixture. Similar treatment of the longer chain derivative **3** yields the mixture of rotaxanes **5a** and **5b** (15% isolated yield). However, the CD-free amide coupling product could not be detected as a reaction product from **3**. This is probably a reflection of the lower aqueous solubility of **3** compared to **2**.

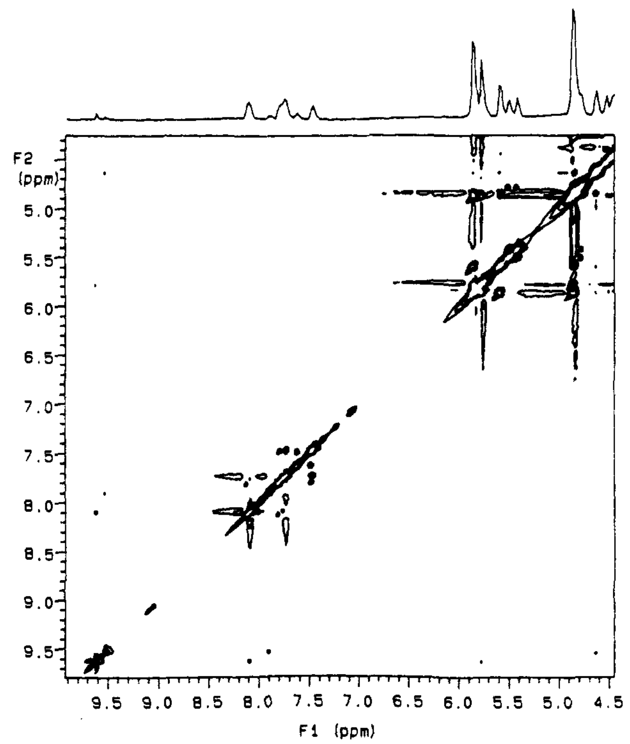


Figure 1. Low-field portion of the NOESY 2D NMR spectrum of compound **4**.

The structural assignment of **4** and **5** is justified by the following findings: (1) The high-field (400-MHz) ^1H NMR spectrum of both compounds is consistent with a species possessing the required number of subunits. (2) Thin-layer chromatography of **5** on silica plates [solvent: acetone/water (4:1)] shows a single spot, which has an R_f value (0.76) different from those of any of the individual components; for instance, **3** and potassium 5-amino-2-naphthalenesulfonate have R_f values of 0.36 and 1.0 under identical conditions. (3) The methylene resonances in the ^1H NMR spectra of **4** and **5** are shifted and broadened as they are in the spectra of α-CD complexes of **1** (when $n \geq 6$), which are known to be chain-centered.[5] (4) The ^1H NMR spectrum of **4** exhibits split resonances for both the amidic proton and the methyl groups on the quaternary nitrogen. The NOESY 2D NMR spectrum clearly shows (see Figure 1) that the low-field amidic proton signal at 9.6 ppm correlates with the resonances of the secondary hydroxyl groups on the wider opening of the CD. On the other hand, the high-field amidic proton signal at 9.5 ppm correlates with the primary hydroxyl groups on the narrower opening of the CD. This provides compelling evidence not only for the proposed rotaxane structures but also for the existence of the CD-positional isomers **4a** and **4b** as depicted in Scheme II.[7] Compounds **4** and **5** are the first reported examples of CD-based asymmetric rotaxanes. In fact, due to the charge on each of the two capping subunits, the asymmetry confers zwitterionic character to these unique structures. The zwitterionic nature, as well as the polarity of the hydroxyl groups on the CD rims, accounts for the marked hygroscopic character of both rotaxanes. To the best of our knowledge, this is the first time that isomers based on the ori-

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(2) Ogino, H. *J. Am. Chem. Soc.* **1981**, *103*, 1303.

(3) Yamanari, K.; Shimura, Y. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 2283. Several rotaxanes reported on this work are not completely symmetric because the end (capping) groups show optical isomerism.

(4) Ventaka, T.; Rao, S.; Lawrence, D. S. *J. Am. Chem. Soc.* **1990**, *112*, 3614.

(5) Isnin, R.; Salam, C.; Kaifer, A. E. *J. Org. Chem.* **1991**, *56*, 35.

(6) We have measured the binding constant between **2** and α-CD in acidic and neutral media. At a pH of 2.6, at which the carboxylic acid is fully protonated, the binding constant was found to be 425 M^{-1}. Conversely, at a pH of 8.0, at which the carboxylic acid is ionized, the binding constant was determined to be 71 M^{-1}.

(7) The possibility that the observed NMR splittings resulted from the CD shuttling back and forth along the alkyl chain was ruled out by the lack of spectral sensitivity to temperature changes. The relative peak areas of both amidic protons indicate that the ratio of isomers in the mixture is approximately 6:4 (**5a**/**5b** and **4a**/**4b**). Elemental analyses (C & H) were within 0.30% of theory for the **5a**/**5b** and **4a**/**4b** mixtures (see supplementary material).

entation of the CD receptor have been observed. These findings are of special relevance to the general area of cyclodextrin complexation because they suggest that threaded CD inclusion complexes, such as those formed by α-CD with alkyl tails, might actually be a mixture of two isomers having different CD orientations. Finally, it is also noteworthy that the presence of the ferrocene subunit affords electroactivity to these rotaxanes.[8]

This work demonstrates a simple, step-by-step, synthetic approach to complicated CD-based rotaxanes which is essentially based on the limited size selectivity provided by CD receptors. Yields are higher than expected for rotaxane synthesis owing to the use of aqueous reaction mixtures to maximize CD–substrate interactions. This method is rather general and is likely to produce a diversity of rotaxane structures having threaded CDs.

Acknowledgment. R.I. gratefully acknowledges the Malaysian Petroleum Company (PETRONAS) for a graduate fellowship. Support of this research by the National Science Foundation (CHE-9000531) is gratefully acknowledged. The purchase of the NMR and MS spectrometers was made possible by grants from the NIH (RR-03351 and RR-04680, respectively).

Supplementary Material Available: Experimental details for the synthesis of **2–6** and ^1H NMR spectra of **4** and **6** (5 pages). Ordering information is given on any current masthead page.

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[8] For other recent examples of electroactive rotaxanes, see: Anelli, P. L.; Ashton, P. R.; Ballardini, R.; Balzani, V.; Delgado, M.; Gandolfi, M. T.; Goodnow, T. T.; Kaifer, A. E.; Philip, D.; Pietraszkiewicz, M.; Prodi, L.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Vicent, C.; Williams, D. J. *J. Am. Chem. Soc.*, in press. Stoddart, and co-workers have also recently synthesized a fascinating rotaxane in which a tetracationic "bead" moves back and forth between two identical "stations", thus behaving as a molecular shuttle: Anelli, P. L.; Spencer, N.; Stoddart, J. F. *J. Am. Chem. Soc.* **1991**, *113*, 5131.

Solution Structure Elucidation of Early-Transition-Metal Polyoxoalkoxides Using ^{17}O Nuclear Magnetic Resonance Spectroscopy

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Early-transition-metal d^0 alkoxides have been known for over a century, but the formulas and structures of polyoxoalkoxides formed in solution upon hydrolysis are unknown despite extensive investigation.[2] All investigations have been frustrated by the absence of a technique capable of characterizing complex mixtures of polynuclear metal oxoalkoxides in solution. As a result, little is known about the principles governing hydrolysis/condensation pathways, an issue of both scientific and technological interest.[3] We have developed a simple technique for characterizing early-transition-metal polyoxoalkoxides in solution that involves ^{17}O NMR spectroscopy[4] of these species selectively enriched in ^{17}O at their oxide (as opposed to alkoxide) oxygen sites. Here, we describe the application of this technique to Ti(IV) polyoxoalkoxides.

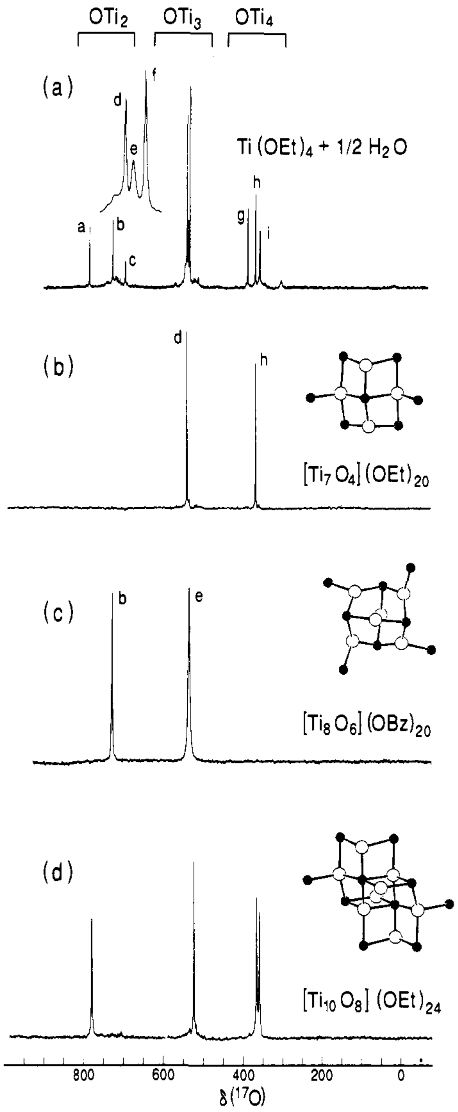

Figure 1. ^{17}O FTNMR (40.7 MHz) spectra of (a) 0.5 M $Ti(OEt)_4$ in $^1/_3$ v/v $CH_3C_6H_5/EtOH$ after addition of $^1/_2$ equiv of 40 atm % ^{17}O-enriched water, (b) selectively enriched $[Ti_7O_4](OEt)_{20}$ in toluene, (c) selectively enriched $[Ti_{10}O_8](OEt)_{24}$ in toluene. The spectral inset in part a is a horizontal expansion of the δ 525–545 region. The structural insets in parts b–d show the metal oxide core structures of the oxoalkoxides under examination, where small filled circles represent titanium centers and large open circles represent oxygen centers. Chemical shifts of principal resonances relative to fresh tap water are as follows: (a) δ 783 (a), 725 (b), 693 (c), 537 (d), 534 (e), 529 (f), 384 (g), 364 (h), 353 (i); (b) δ 537 (d) and 365 (h); (c) δ 726 (b) and 533 (e); and (d) δ 782, 525, 367, and 360.

Hydrolysis of 0.5 M $Ti(OEt)_4$ in $^1/_3$ v/v $CH_3C_6H_5/EtOH$, Et = CH_2CH_3, with $^1/_2$ equiv of 40 atom % ^{17}O-enriched H_2O yielded a clear solution, whose ^{17}O NMR spectrum is shown in Figure 1a. The nine principal resonances labeled a–i in Figure 1a have chemical shifts that are grouped together in three distinct regions, δ 250–450, 450–650, and 650–850. When similar solutions were prepared using slightly different amounts of water, the intensities of certain ^{17}O resonances were observed to vary in a correlated fashion, strongly suggesting their assignment to a single species. Specifically, resonances d (δ 537) and h (δ 364) as well as resonances b (δ 725) and e (δ 534) appeared to arise from distinct complexes that have been identified as $[Ti_7O_4](OEt)_{20}$ and $[Ti_8O_6](OEt)_{20}$, respectively, as outlined below.

Hydrolysis of $Ti(OEt)_4$ in ethanol with $^2/_3$ equiv of H_2O and

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[1] (a) University of Nebraska. (b) University of Illinois.

[2] Bradley, D. C.; Mehrotra, R. C.; Gaur, D. P. *Metal Alkoxides*; Academic Press: New York, 1978.

[3] Brinker, C. J.; Scherer, G. W. *Sol-Gel Science*; Academic Press: San Diego, 1990.

[4] Kintzinger, J.-P. *NMR: Basic Princ. Prog.* **1981**, *17*, 1.

0002-7863/91/1513-8190$02.50/0