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Synthesis and Characterization of a Persistent Paramagnetic Rotaxane Based on α-Cyclodextrin

Elisabetta Mezzina,* Michela Fanì, Fiammetta Ferroni, Paola Franchi, Manuel Menna, and Marco Lucarini*

Department of Organic Chemistry "A. Mangini", University of Bologna, Via San Giacomo 11, I-40126 Bologna, Italy

marco.lucarini@unibo.it; elisabetta.mezzina@unibo.it

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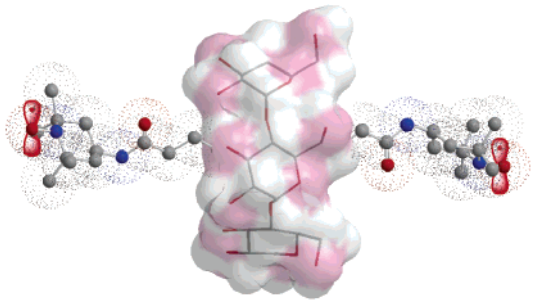

The synthesis and spectroscopic properties of a novel paramagnetic [2]rotaxane is described. This rotaxane is made from molecules having an alkyl chain flanked by 2,2,6,6-tetramethylpiperidine-*N*-oxyl (TEMPO) groups. Complexation of sebacoyl chloride by α-cyclodextrin followed by reaction with a bulky aminonitroxide resulted in the trapping of the cyclodextrin, threaded by the alkyl chain, thus generating the rotaxane structure. The structure of the paramagnetic [2]rotaxane was fully characterized by ESI-MS, 1D and 2D NMR and ESR spectroscopy.

Introduction

Nitroxide radicals are of great importance and interest in many fields of chemistry and related sciences. The technological applications of stable free radicals include the biomedical field (spin label,[1] spin traps,[2] antioxidants[3]), chemical synthesis (mediators in "living" free radical polymerization[4] and catalysts in new aerobic oxidation process[5]), and material chemistry (building blocks for molecular based magnetic materials[6]).

Recently, much attention has been focused on interlocked molecules such as rotaxanes because they are considered to be a typical prototype of molecular machines bearing a rotor and an axle in the molecule.[7] Because cyclodextrins (CDs) have cavities with depths around 5 Å, they are able to be threaded onto a long axle and to slide along a chain or to rotate around an axle. Actually, several examples of [2]rotaxane incorporating CDs as the ring components have been reported in the literature.[8,9]

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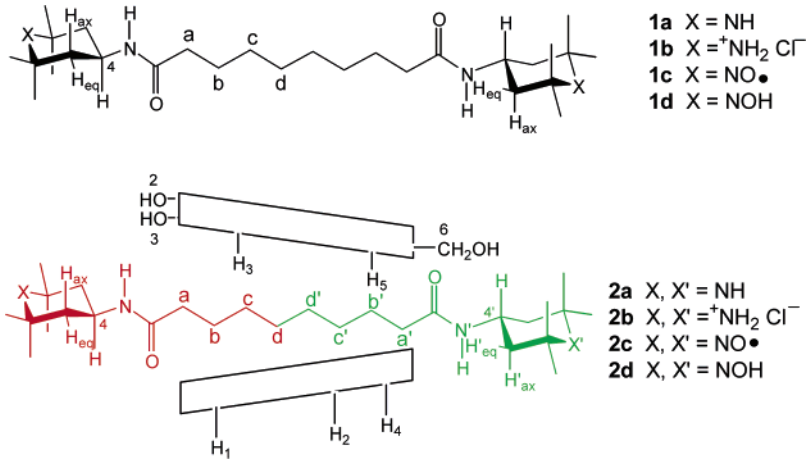
SCHEME 1



As a part of our continuing studies on the characterization of new supramolecular architectures containing open-shell molecules,[10] here we report the synthesis and complete spectroscopic characterization of an α-cyclodextrin-based rotaxane (**2c**) in which the axle molecule is a persistent paramagnetic thread made of a nitroxide biradical. In our view, the presence of persistent radical centers in a rotaxane is potentially an attractive functionality that can be exploited to modulate the behavior of molecular devices.

Scheme 1 shows the structure of the radical guest **1c** used as a dumbbell in this synthesis. This symmetric rod is formed by the amidic linkage of an α-*ω* difunctionalized octamethylene unit chain with two piperidinoxyl moieties, each containing one unpaired electron. Among the many possible molecular fragments containing a radical functionality, we have decided to employ the 2,2,6,6-tetramethylpiperidine-*N*-oxyl (TEMPO) group as steric trap moiety because of its many possible applications.[1−6] To the best of our knowledge **2c** represents the first example of a persistent [2]rotaxane organic radical.

Results and Discussion

Evidence that the TEMPO stopper is bulky enough to act as an end-cap group of a rotaxane consisting of α-CD was preliminarily obtained by recording the ESR spectrum of **1c** in the presence of natural cyclodextrins having different sizes (α-, *β*-, and *γ*-CD; see Figure 1). Whereas in the presence of α-CD the ESR spectrum is characterized by five lines similar to what is observed in water (Figure 1, spectra a and b), in the presence of *β*- and *γ*-CD, the number of ESR signals reduces essentially to three lines (Figure 1, spectra c and d).

These spectral changes can be explained in terms of spin exchange occurring between the two paramagnetic centers. In the absence of spin exchange, the biradical **1c** behaves as two single nitroxide radicals and the ESR spectrum consists of three lines due to the individual spins coupled with the nitrogen nucleus with a hyperfine splitting constant a_N. When the electrons are coupled (J) more strongly to each other than to either nitrogen nucleus, that is, when $J \gg a_N$, the spectrum contains five lines, separated by $a_N/2$.[11] The long chain present in **1c** allows the biradical to adopt several conformations. From the point of view of the spin exchange phenomenon, we can effectively consider two conformations, i.e., one, a straight-chain conformation, in which the probability of collision for the two radical fragments is negligible, and two, a folded conformation, where there is a finite probability of collision. In the first conformation the exchange is zero, and in the second it is strong. While in solution both of them have a significant probability of occurring, we expect that inclusion of the alkyl chain of the biradical in the inner cavity of a CD host fixes it in an extended conformation, i.e., a conformation in which no electron exchange can occur between the two radical subunits, giving rise to a three-line spectrum. The ESR spectra observed in the presence of *β*- or *γ*-CD are, therefore, a clear indication that the "extended conformation" of the biradical is predominant in such conditions as a result of the inclusion of the biradical by CDs.

On the other hand, the five-line spectrum[12] observed in the presence of α-CD suggests that the primary face of α-CD is too small to permit the threading of the biradical inside the cavity, leaving the nitroxide in the bulk solution where it may adopt a folded conformation. On the basis of these results we conclude that it is possible to construct an α-CD-based [2]rotaxane having the 2,2,6,6-tetramethylpiperidine-*N*-oxyl ring as the end-cap group.

Because paramagnetic species yield NMR spectra of very low resolution, making structural assignment rather difficult, we initially prepared and characterized a [2]rotaxane having the diamagnetic structurally related 2,2,6,6-tetramethylpiperidine ring as stopper (**2a**). Among the different strategies available for the construction of a [2]rotaxane structure we chose the threading approach,[9f] which requires carrying out the self-assembly and the subsequent covalent modifications in aqueous media, i.e., the environment that is by far the best when considering the binding of guest molecules by CDs. Sebacoyl chloride is treated with an excess of α-CD and 2 equiv of 4-amino-2,2,6,6-tetramethylpiperidine in basic water giving rise to rotaxane **2a** in 5.4% isolated yields. The CD-free products resulting from the direct condensation of uncomplexed sebacoyl chloride with 1 or 2 equiv of 4-amino-2,2,6,6-tetramethylpip-

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(12) The heights of the lines are not in the expected ratio of 1:2:3:2:1 because the intramolecular motion modulates the value of *J*, which produces an alternating line width effect.

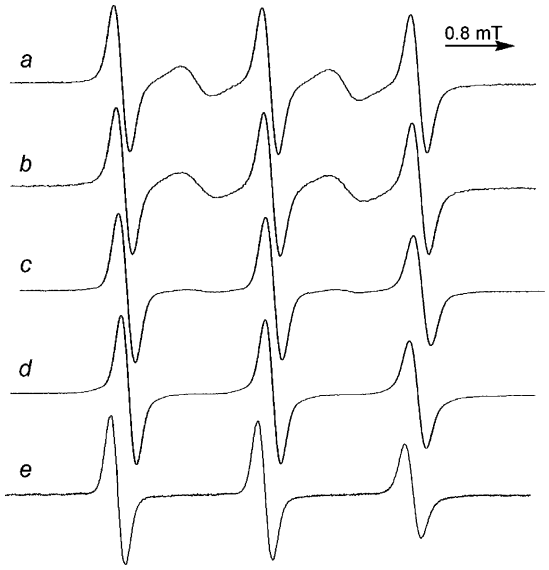

FIGURE 1. ESR spectra of **1c** (0.2 mM) recorded at 50 °C in water/MeOH (90/10) (a, a_N = 1.68 mT) and in the presence of α-CD 47 mM (b, a_N = 1.68 mT), β-CD 10 mM (c, a_N = 1.67 mT), and γ-CD 17 mM (d, a_N = 1.66 mT). The ESR spectrum (e) represents that of **2c** recorded in water at 298 K.

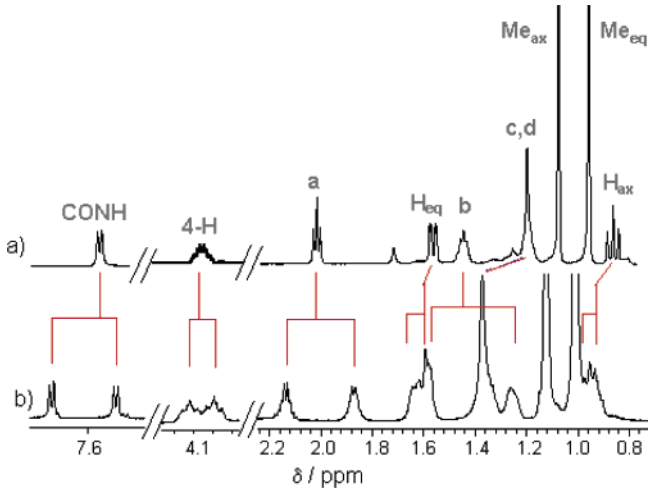

FIGURE 2. Partial ^{1}H NMR spectra (600 MHz, DMSO-d_6, 298 K) of thread **1a** (a) and rotaxane **2a** (b). The signals are assigned on the basis of 2D ROESY experiments by using the labels reported in Scheme 1. The signals of the thread in the rotaxane (spectrum b) appear in most cases as split couples of signals because of the presence of the asymmetric rotor (α-CD) over the alkyl chain.

eridine represent the main unwanted products of the reaction. The [2]rotaxane **2a** is purified by the above side products by using reverse phase and exclusion chromatographies (see Experimental Section).

Structural assignment of rotaxane **2a** is justified on the basis of ESI-MS and 1D and 2D NMR analyses. The formation of the interlocked molecule is clearly apparent when comparing ^{1}H NMR spectral data of the thread **1a** recorded in DMSO-d_6 with those of rotaxane **2a** (see Figure 2). In particular, the peaks due to the protons located on the outer part of the linear chain (a, b, and C(O)NH) and on the heterocyclic ring (4-H, H$_{ax}$, and H$_{eq}$) split into two well separated signals as a consequence of the different environment experienced when the nonsymmetrical cavity of the macrocycle wraps the thread. The signals corresponding to the methyl and c, d methylene protons of **2a** are characterized by singlets resonating at lower field with respect to the free molecule. Significant differences in the resonance frequencies of the free and interlocked α-CD are also evident when comparing the corresponding ^{1}H NMR spectra. As an example in Figure 3 is reported the cyclodextrin ^{1}H NMR region of a solution containing approximately an equal amount of rotaxane **2a** and free α-CD. It is evident that threading of the alkyl chain into the CD cavity resulted in a significant displacement of the proton signals of the macrocyclic host, giving rise to sharply separate signals.

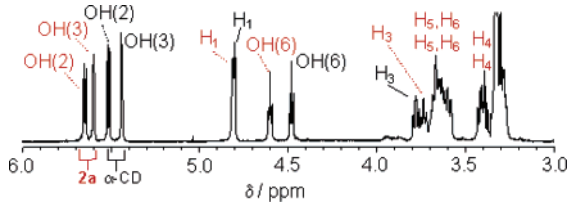

FIGURE 3. ^{1}H NMR cyclodextrin region of a mixture containing almost equal amounts of rotaxane **2a** and free α-CD. The proton signals of α-CD engaged in the rotaxane and of the free macrocyclic ring are indicated by red and black labels, respectively.

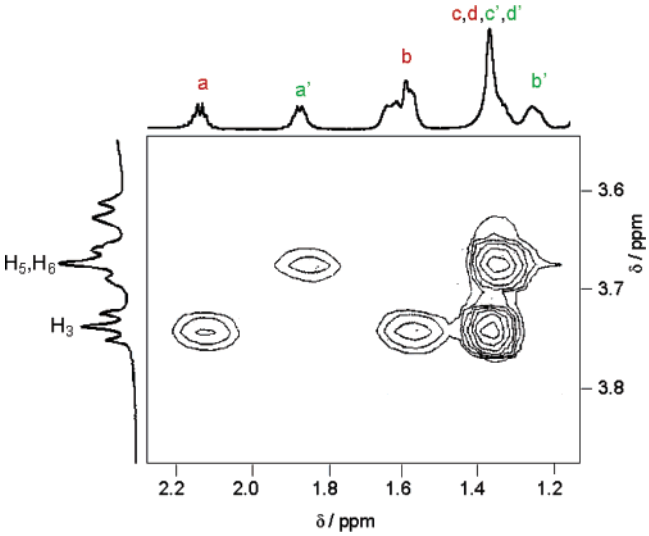

FIGURE 4. 2D ROESY region (600 MHz, DMSO-d_6, 298 K) of rotaxane **2a**. The contour plot reflects the intermolecular cross-peaks connecting the methylene protons of the thread and the protons of α-CD (H$_3$, H$_5$, and H$_6$; see Scheme 1 for label definitions). Each resonance corresponding to the a and b alkyl protons of the thread is split into a pair of signals, one shielded and the other deshielded respect to the signal of the free thread **1a**. Within the couples of signals, the deshielded peak displays interaction with H$_3$, while the shielded one correlates with H$_5$ and/or H$_6$ of α-CD, this being a clear indication of the position of the cyclodextrin respect to the thread.

Strong evidence for the formation of a mechanical interlocked structure is also obtained by 2D ROESY experiments. In Figure 4 are shown the strong intermolecular correlations found in the rotaxane **2a** between the methylene protons of the axle molecule and those of α-CD. Of particular interest is the observation that the inner H$_3$ protons of α-CD show ROE correlation exclusively with the downfield shifted alkyl chain protons (a, b) of the thread, while the upfield shifted protons (a′, b′) show cross-peaks only with the protons of α-CD at the 5- and/or 6-position. The central protons of the thread (c, c′, d, d′) are instead found to correlate with both the α-CD inner protons. These results

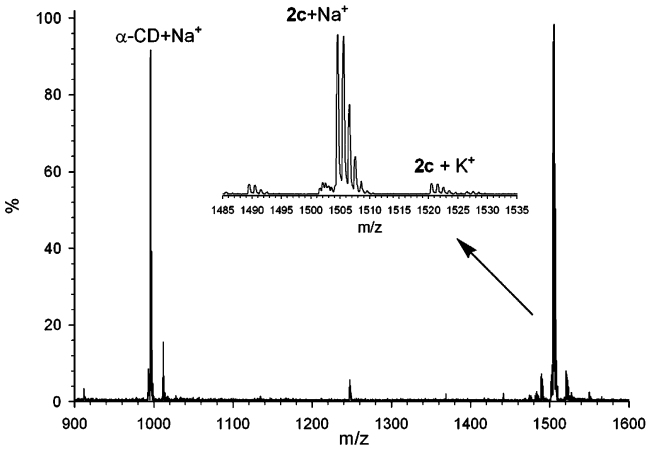

FIGURE 5. Positive ESI spectrum of a water solution containing rotaxane **2c**. The spectrum has been recorded by using the following instrumental settings: positive ions; desolvation gas (N_2) 230 L/h; cone gas (skimmer) 50 L/h; desolvation temp 150° C; capillary voltage 2.8 kV; cone voltage 120 V; hexapole extractor 3 V. The signal at 995.6 due to the unthreaded α-CD is always present when using a cone voltage > 100 V.

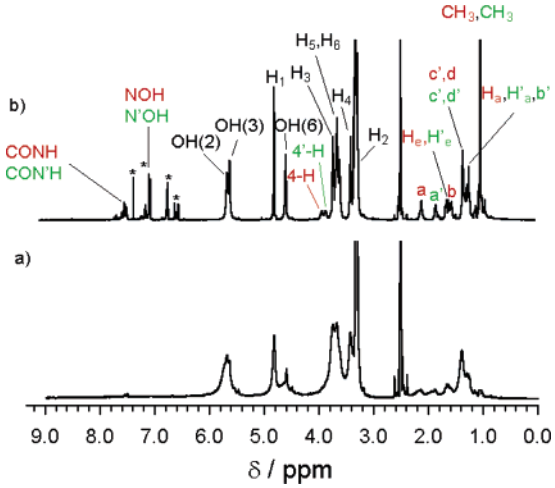

FIGURE 6. ^{1}H NMR spectra (600 MHz, DMSO-d_6, 298 K) of rotaxane **2c** (a) and rotaxane **2d** (b). The spectrum b is obtained by adding some phenylhydrazine directly in the NMR tube containing a solution of rotaxane **2c**. Star symbols refer to the signals of phenylhydrazine. The signals are assigned on the basis of 2D ROESY experiments by using the labels reported in Scheme 1. In both spectra red and green letters represent the proton signals facing the larger and smaller rim of α-CD rotor, respectively. Black letters indicate proton signals of the rotor (α-CD engaged in the rotaxane).

show that the thread is mechanically encapsulated by the α-CD with the secondary hydroxyl groups in the macrocycle (i.e., the larger rim) facing the tetramethylpiperidine moiety bound to the deshielded part of the linear chain.[13]

On the basis of these promising results we have repeated the above synthetic procedure to prepare the paramagnetic rotaxane **2c**. Actually, treatment of 4-amino-TEMPO with sebacoyl chloride in the presence of an excess of α-CD yields rotaxane **2c** in 5% isolated yield. Evidence for the formation of rotaxane **2c** is obtained on the basis of ESI-MS (see Figure 5), NMR, and ESR results. As expected **2c** yields NMR spectra of very low resolution, making structural assignment rather difficult (see Figure 6a).[14] To render the paramagnetic rotaxane **2c** suitable for NMR analysis, it is quantitatively converted into the analogous *N*-hydroxylamine derivative (**2d**) by adding directly inside the NMR tube a stoichiometric amount of phenylhydrazine.[15] In Figure 6b is reported the complete ^{1}H NMR spectra (600 MHz, DMSO-d_6, 298 K) of the rotaxane **2c** after its reduction to **2d**. The spectrum of **2d** show features very similar to those found in **2a**. In particular, the signals marked by red letters refers to the protons of the thread facing the larger rim of α-CD, whereas the peaks of protons closer to the smaller rim of the macrocycle are labeled by green letters. The proton signals of α-CD engaged in the rotaxane are indicated by black letters (see Scheme 1 for labels definition).

2D ROESY experiments give rise to ROE correlations very similar to those found in the spectra of **2a**, confirming the correct assignments of the signals (see Supporting Information).

The room-temperature ESR spectrum of rotaxane **2c** in water ($a_N = 1.705$ mT, $g = 2.0057$, see Figure 1e) consists of three lines as expected for a nitroxide biradical in the extended conformation in which the TEMPO fragments behave as two single nitroxide radicals. The high field ESR line of **2c** is characterized by a lower height, presumably as a result of the slower motion in solution of the rotaxane biradical, resulting in incomplete averaging of the anisotropic components of the hyperfine and *g*-tensors. Alternatively, the broadening of the high field line can be attributed to the unresolved overlapping of the spectral lines of the two unequivalent nitroxide units in **2c**.

Finally, the thermal stability of the paramagnetic rotaxane has been examined by heating at 60 °C for 14 days a water solution of **2c**. The ESR spectra recorded at different time intervals do not show any particular difference, indicating that dethreading of the biradical in the bulk solution, resulting in a five-line ESR spectrum, is not taking place under the reported conditions.

Conclusions

In conclusion, a [2]rotaxane capped by persistent nitroxyl functions has been prepared for the first time, and its structure has been unequivocally determined. Consequently, a new kind of very stable paramagnetic rotaxanes has been constructed in solution and in the solid state. We believe that the proposed procedure for the construction of mechanical interlocked organic free radicals may represent a promising route for the preparation of more complex paramagnetic supramolecular architectures whose properties can be exploited in many technological applications. Work in this direction is under investigation.

Experimental Section

ESR Measurements. The ESR spectra have been recorded by using the following instrument settings: microwave power 0.79 mW, modulation amplitude 0.04 mT, modulation frequency 100 kHz, scan time 180 s, 2 K data points.

(13) This interpretation of the spectral data was also corroborated by the detection of weak cross-peaks relating hydroxyl protons of the larger rim with the downfield shifted CH_2 (a) and heterocyclic H_{eq} of the rod. Similarly, primary hydroxyl protons (smaller rim) show correlation with upfield shifted protons H'_{ax}, CH_2 (a′) and CON′H (see Supporting Information).

(14) Contrary to the behavior found in the mechanical interlocked α-CD, the proton signals of free α-CD added to the solution containing the paramagnetic rotaxane **2c** (1 mM) do not show line broadening.

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Synthesis of 2a and 2b. In a typical experiment α-CD (1.5 g, 1.54 mmol) and 4-amino-2,2,6,6-tetramethylpiperidine (4-amino-TMP) (0.39 g, 2.5 mmol) are dissolved in 20 mL of 1 M sodium hydroxide and cooled to 0 °C. Sebacoyl chloride (0.21 mL, 1 mmol) and 2 mL of 1 M sodium hydroxide are added simultaneously in 10 equal portions, at 3 min intervals, with stirring. The solution is stirred for 24 h at room temperature and extracted with CH_2Cl_2 to remove the free thread **1a**. The aqueous solution is acidified with concentrated HCl (pH ≈ 4), extracted with CH_2Cl_2 to remove sebacic acid, then treated with 1 M NaOH until pH 8−9, and again extracted with CH_2Cl_2 to partially remove the *N*-TMP monoamide of sebacic acid (10-oxo-10-[(2,2,6,6-tetramethyl-4-piperidinyl)-amino]decanoic acid, **3a**) and the unreacted amine. The concentrated solution gives a white solid that is suspended twice in methanol (20−25 mL) with stirring for 24 h at room temperature to decrease the amount of α-CD from the reaction mixture. The filtrate is concentrated and the powder is analyzed by ESI-MS spectrometry and by TLC. ESI-MS spectrum reveals peaks corresponding to rotaxane **2b**, α-CD, **3a**, and 4-amino TMP. TLC is performed on RP18 F_{254} plates. The eluent is MeOH−H_2O 1:1 (v:v) and the spots are detected by exposing the plates to iodine vapor (to detect the unwanted free products) and then by charring with heat spraying the plate with 50% methanolic sulfuric acid. Charring is the indication for the presence of cyclodextrin moieties ($R_{f_{a\text{-}CD}}$ 0.72; $R_{f_{2b}}$ 0.92). The crude obtained (ca. 0.6 g) is separated by reverse-phase C18 silica column chromatography (length 25 cm, i.d. 3 cm), eluting with MeOH−H_2O 1:1. The separation gives a mixture of rotaxane and α-CD (0.3 g) that is further chromatographed by gel filtration over a Sephadex G-15 column (length 45 cm, i.d. 2 cm) using distilled water as eluent. In both chromatographic separations fractions of 1−2 mL are collected. Rotaxane **2b** (82 mg) is recovered pure in 5.4% yield. Rotaxane **2a**, the free amine form of rotaxane **2b**, is recovered adding 1 M NaOH to the aqueous solution containing the reaction mixture until pH = 10−11 and following the procedure described above.

Compound 2a: sticky transparent solid; ^{1}H NMR (600 MHz, DMSO-d_6, 298 K, relative to the solvent peak) δ 7.70 (d, J = 7.2 Hz, 1H, NHCO), 7.52 (d, J = 7.2 Hz, 1H, NHCO), 5.66 (d, J = 6.0 Hz, 6H, OH(2)), 5.60 (br s, 6H, OH(3)), 4.81 (d, J = 3.6 Hz, 6H, H_1), 4.61 (t, J = 5.4 Hz, 6H, OH(6)), 4.01 (m, 1H, 4-H), 3.95 (m, 1H, 4′-H), 3.73 (t, J = 9.6 Hz, 6H, H_3), 3.59−3.70 (m, 18H, H_5, H_6), 3.42 (t, J = 9.0 Hz, 6H, H_4), 3.29 (dd, J = 9.6, 3.6 Hz, 6H, H_2), 2.13 (m, 2H, CH_2 (*a*)), 1.87 (m, 2H, CH_2 (*a*′)), 1.55−1.67 (m, 6H, H_{eq}, H'_{eq}, CH_2 (*b*)), 1.36 (m, CH_2 (*c*, *d*, *c*′, *d*′)), 1.24 (m, 2H, CH_2 (*b*′)), 1.12 (s, 12H, Me_{ax}), 1.01 (s, 6H, Me_{eq}), 1.00 (s, 6H, Me_{eq}), 0.96 (dd, J = 12.0, 3.8 Hz, 2H, H_{ax}), 0.92 (dd, J = 12.0, 6.6 Hz, 2H, H'_{ax}); positive ESI-MS m/z 1452.4 (**2a** + H)$^+$, 1474.4 (**2a** + Na)$^+$, 995.6 (α-CD + Na)$^+$, 726.5 (**2a** + 2H)$^{2+}$, 737.4 (**2a** + H + Na)$^{2+}$, 748.5 (**2a** + 2Na)$^{2+}$; negative ESI-MS m/z 1450.4 (**2a** − H)$^-$, 724.4 (**2a** − 2H)$^-$.

Compound 2b: sticky transparent solid; ^{1}H NMR (600 MHz, DMSO-d_6, 298 K, relative to the solvent peak) δ 9.11 (1H, br s, NH^+), 9.04 (br s, 1H, NH^+), 8.07 (br s, 1H, NH^+), 7.97 (br s, 1H, NH^+), 7.91 (d, J = 7.2 Hz, 1H, NHCO), 7.82 (d, J = 7.2 Hz, 1H, NHCO), 5.65 (d, J = 7.2 Hz, 6H, OH(2)), 5.59 (d, J = 2.4 Hz, 6H, OH(3)), 4.81 (d, J = 3.6 Hz, 6H, H_1), 4.58 (t, J = 6.0 Hz, 6H, OH(6)), 4.13 (m, 1H, 4-H), 4.04 (m, 1H, 4′-H), 3.73 (dt, J = 9.6, 2.4 Hz, 6H, H_3), 3.59−3.70 (m, 18H, H_5, H_6), 3.43 (t, J = 9.0 Hz, 6H, H_4), 3.31 (ddd, J = 9.6, 7.2, 3.6 Hz, 6H, H_2), 2.17 (m, 2H, CH_2 (*a*)), 1.91 (m, 4H, CH_2 (*a*′), H_{eq}), 1.82 (bd, J = 12.6 Hz, 2H, H'_{eq}), 1.61 (m, 2H, CH_2 (*b*)), 1.28−1.50 (m, 36H, H_{ax}, H'_{ax}, Me, CH_2 (*c*, *d*, *c*′, *d*′)), 1.18 (m, 2H, CH_2 (*b*′)); positive ESI-MS m/z 1452.4 (**2a** + H)$^+$, 1474.4 (**2a** + Na)$^+$, 995.6 (α-CD + Na)$^+$, 726.5 (**2a** + 2H)$^{2+}$, 737.4 (**2a** + H + Na)$^{2+}$, 748.5 (**2a** + 2Na)$^{2+}$; negative ESI-MS m/z 1450.4 (**2a** − H)$^-$, 1486.3 (**2b** − H − HCl)$^-$, 760.4 (**2b** − 2H)$^-$.

Synthesis of 2c. The rotaxane **2c** is obtained by reacting α-CD (1.5 g, 1.54 mmol), 4-amino-2,2,6,6-tetramethylpiperidine-*N*-oxyl (4-amino-TEMPO) (0.34 g, 2 mmol) with sebacoyl chloride (0.21 mL, 1 mmol) following the procedure described above. TLC spots ($R_{f_{2c}}$ 0.62, eluent MeOH/H_2O 1/1, v/v) is detected by UV lamp or exposing the plates to iodine vapor and then by charring with heat spraying the plate with 50% methanolic sulfuric acid. The crude obtained is separated by reverse-phase C18 silica column chromatography and by gel filtration over a Sephadex G-15 column under the same conditions reported for **2a** and **2b**. Rotaxane **2c** (74 mg) is obtained in 5.0% yield. A small amount of the mono reducted *N*-hydroxy derivative of **2c** can also be present in the isolated product. Oxidation of these byproducts in order to obtain pure **2c** can be achieved by heating the sample at 70 °C for 2 days.

Compound 2c: orange solid; ^{1}H NMR (600 MHz, DMSO-d_6, 298 K, relative to the solvent peak) δ 5.60−5.84 (m, 12H, OH(2), OH(3)), 4.83 (br s, 6H, H_1), 4.60 (br s, 6H, OH(6)), 3.50−3.90 (m, 18H, H_3, H_5, H_6), 3.20−3.50 (m, 12H, H_4, H_2), 2.13 (m, 2H, CH_2 (*a*)), 1.87 (m, 2H, CH_2 (*a*′)), 1.57−1.70 (m, 6H, H_{eq}, H'_{eq}, CH_2 (*b*)), 1.20−1.50 (m, 14H, H_{ax}, H'_{ax}, CH_2 (*c*, *d*, *b*′, *c*′, *d*′)); IR (Nujol) 3360, 1644, 1562 cm^{-1}; positive ESI-MS m/z 1504.3 (**2c** + Na)$^+$, 995.6 (α-CD + Na)$^+$, 763.5 (**2c** + 2Na)$^{2+}$; negative ESI-MS m/z 1480.4 (**2c** − H)$^-$

Rotaxane **2d** is obtained by reduction with phenylhydrazine of the NMR sample containing **2c**.

Compound 2d: ^{1}H NMR (600 MHz, DMSO-d_6, 298 K, relative to the solvent peak) δ 7.54 (d, J = 7.2 Hz, 1H, NHCO), 7.50 (d, J = 7.2 Hz, 1H, NHCO), 7.09 (s, 1H, NOH), 7.06 (s, 1H, NOH), 5.65 (d, J = 7.0 Hz, 6H, OH(2)), 5.60 (d, J = 2.4 Hz, 6H, OH(3)), 4.81 (d, J = 3.2 Hz, 6H, H_1), 4.60 (t, J = 6.0 Hz, 6H, OH(6)), 3.94 (m, 1H, 4-H), 3.87 (m, 1H, 4′-H), 3.73 (t, J = 9.3 Hz, 6H, H_3), 3.58−3.70 (m, 18H, H_5, H_6), 3.41 (t, J = 9.0 Hz, 6H, H_4), 3.29 (m, 6H, H_2), 2.13 (m, 2H, CH_2 (*a*)), 1.86 (m, 2H, CH_2 (*a*′)), 1.68 (m, 2H, H_{eq}), 1.63 (m, 2H, H'_{eq}), 1.58 (m, 2H, CH_2 (*b*)), 1.37 (m, CH_2 (*c*, *d*, *c*′, *d*′)), 1.24−1.34 (m, 6H, H_{ax}, H'_{ax}, CH_2 (*b*′)), 1.05 (s, 24H, Me_{ax}, Me_{eq}); ^{13}C NMR (125 MHz, DMSO-d_6, 298 K, relative to the solvent peak) δ 172.3 (CONH), 172.1 (CONH), 102.0 (α-CD), 81.9 (α-CD), 73.4 (α-CD), 72.2 (α-CD), 71.9 (α-CD), 59.6 (α-CD), 57.8 (2-C), 44.8 (4-C), 44.7 (3-C), 36.4 (CH_2), 36.0 (CH_2), 32.6 (Me), 30.3 (CH_2), 30.0 (CH_2), 29.6 (CH_2), 29.4 (CH_2), 27.3 (CH_2), 25.8 (CH_2), 19.6 (Me).

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Supporting Information Available: ^{13}C NMR spectra of **1d** and **2d**, 2D ROESY spectral regions of rotaxanes **2a** and **2d**, and a schematic representation of intra- and intermolecular ROE correlations found in the rotaxanes **2a**−**d**. This material is available free of charge via the Internet at http://pubs.acs.org.

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