Installation of a Ratchet Tooth and Pawl To Restrict Rotation in a Cyclodextrin Rotaxane

Hideki Onagi,[a] Christopher J. Blake,[a] Christopher J. Easton,*[a] and Stephen F. Lincoln[b]

Abstract: Eight new [2]rotaxanes have been prepared, incorporating an α-cyclodextrin as the rotor, a stilbene as the axle, and trinitrophenyl substituents as capping groups. Strategies have been devised to elaborate these by linking the rotor to the axle, to produce two new [1]rotaxanes. Rotational motion in a selection of these rotaxanes has been investigated through the application of two-dimensional NMR spectroscopy by performing TOCSY, DQF-COSY, ROESY and HMQC experiments. This has shown that a methoxyl group incorporated on the stilbene and a succinamide joining the stilbene and the cyclodextrin behave analogously to a ratchet tooth and pawl, respectively, to restrict rotation.

Keywords: cyclodextrins · molecular devices · molecular dynamics · NMR spectroscopy · rotaxanes

Introduction

Controlling molecular motion is a fundamental aspect of nanotechnology.[1–4] It is the basis of molecular machines such as muscles,[5] switches,[6,7] shuttles,[8] gears,[9] ratchets,[10,11] brakes[12] and motors.[13] Regulating rotational motion is a particular facet of the construction of many of these devices and specially noteworthy examples where this has been achieved are the trypticenyl helicene system, developed by Kelly et al.,[13,14] and the phenanthrylidenes of Feringa and co-workers.[15–17] Achieving the same objective in supramolecular assemblies such as rotaxanes is still a significant challenge.[18,19] Nevertheless, it is an important aim, as part of a broader objective to provide access to functional prefabricated structures, comprising multiple species that are physically interlocked and unable to dissociate. We therefore set out to restrict rotational motion in a cyclodextrin [2]rotaxane.

Cyclodextrins are well known to form host–guest complexes.[20] NMR studies of the anisotropy of the cyclodextrin resonances show that, in such a complex and on the timescale of the experiments, the guest usually rotates freely around the axis of symmetry delineated by the annulus of the cyclodextrin. The dynamic molecular motions of a cinnamate guest included in a range of cyclodextrin hosts have been investigated by Kuroda et al.,[21] by analyzing quadrupolar relaxation times[22] as determined through line shape analysis.[23] The motions were found to be somewhat restricted in complexes having high binding constants, but they were too fast to be observed using general NMR techniques. The only case of restricted guest rotation in a cyclodextrin-based system being observable using conventional NMR spectroscopy was reported by Fujita and co-workers.[24] In the complex of sodium 2-naphthalenesulfonate with a mono-*altro*-β-cyclodextrin, which has a significantly distorted annulus, the shielding and deshielding of the proton resonances of the host showed that the guest does not freely rotate.

Previously we have prepared the rotaxanes **2a** and **2b**, and analyzed their conformations, both in solution and in the solid state.[25,26] In solution, the α-cyclodextrin rotor of **2a** was observed to be rotating freely around the stilbene axle. This was determined through ^{1}H NMR analysis and the observation of only a single set of glucopyranose resonances. By comparison, restricted rotation would be expected to lead to multiple sets of resonances, due to the guest disrupting the six-fold symmetry of the host. Introduction of the methoxyl groups in the rotaxane **2b** had no apparent effect on the rotational motion, as indicated by the simplicity of the ^{1}H NMR spectrum. Therefore, we decided to incorporate a link between the axle and the rotor of **2b**. Our aim was to identify a link that would interact with the adjacent methoxyl substituent, such that they would behave analogously to a ratchet pawl and tooth, respectively (Figure 1), to restrict rotation.

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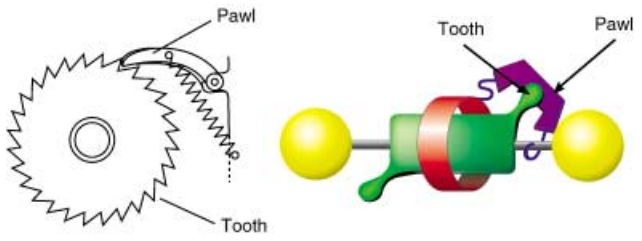

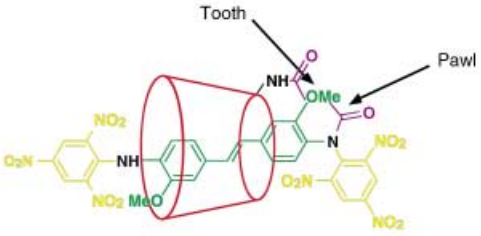

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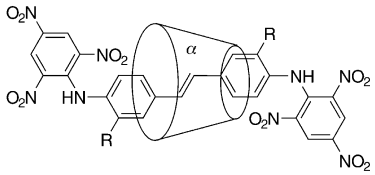
Figure 1. Schematic representation of a tooth and pawl restricting rotational motion in a mechanical ratchet and a cyclodextrin rotaxane.

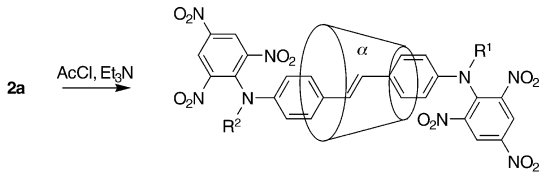


2a R = H
2b R = OMe

Results and Discussion

Initially, the feasibility of elaborating the axle was established, through treatment of the rotaxane **2a** with acetyl chloride. The reaction gave a mixture of the diamide **3a** and the monoamides **3b** and **3c** (Scheme 1), in the ratio about 2:6:1, which were separated through preparative HPLC. ^{1}H NMR signals of the diamide **3a**, at δ 2.28 and 2.34 ppm, were assigned to the acetyl groups adjacent to the ends of the cyclodextrin delineated by the rims of primary and secondary hydroxyl groups, respectively. This assignment was based on the observation of NOE interactions between the resonance at δ 2.34 ppm and that of the adjacent stilbene proton at δ 7.55 ppm, as well as between the resonance at δ 7.55 ppm and that at δ 3.76 ppm corresponding to the C–3 protons of the cyclodextrin glucopyranose rings. The monoamides **3b** and **3c** were distinguished primarily on the basis of the chemical shifts of the resonances for their acetyl groups, by analogy with those of the diamide **3a**. As for the rotaxanes **2a** and **2b**, the simplicity of the ^{1}H NMR spectra of the acetylated rotaxanes **3a–c** shows that rotation of the cyclodextrins around the stilbene axles is not restricted in these systems.

The axle of the rotaxane **2a** is acylated at either or both ends, and acylation followed by attachment of the acylating

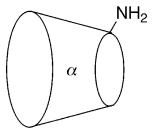


3a $R^1 = R^2 = Ac$
3b $R^1 = Ac$, $R^2 = H$
3c $R^1 = H$, $R^2 = Ac$

Scheme 1.

group to the cyclodextrin would therefore afford a mixture of products. To avoid this it was decided to incorporate the link by initially modifying the cyclodextrin. Accordingly, we investigated the synthesis of a variety of rotaxanes from cyclodextrins substituted with a single masked amino group, anticipating that a bifunctional acylating agent would then be used to attach the cyclodextrin to the axle (Scheme 2). It was necessary to mask the amino group during rotaxane formation, in order to avoid reaction of the modified cyclodextrin with the capping reagent.

6^A-Azido-6^A-deoxy-α-cyclodextrin **5a** and the corresponding amine **4** were prepared using literature procedures.[27–29] Treatment of the amine **4** with acetic anhydride, benzyl chloroformate and di-*tert*-butyl dicarbonate gave derivatives **5b–d**, respectively. Using the conditions employed



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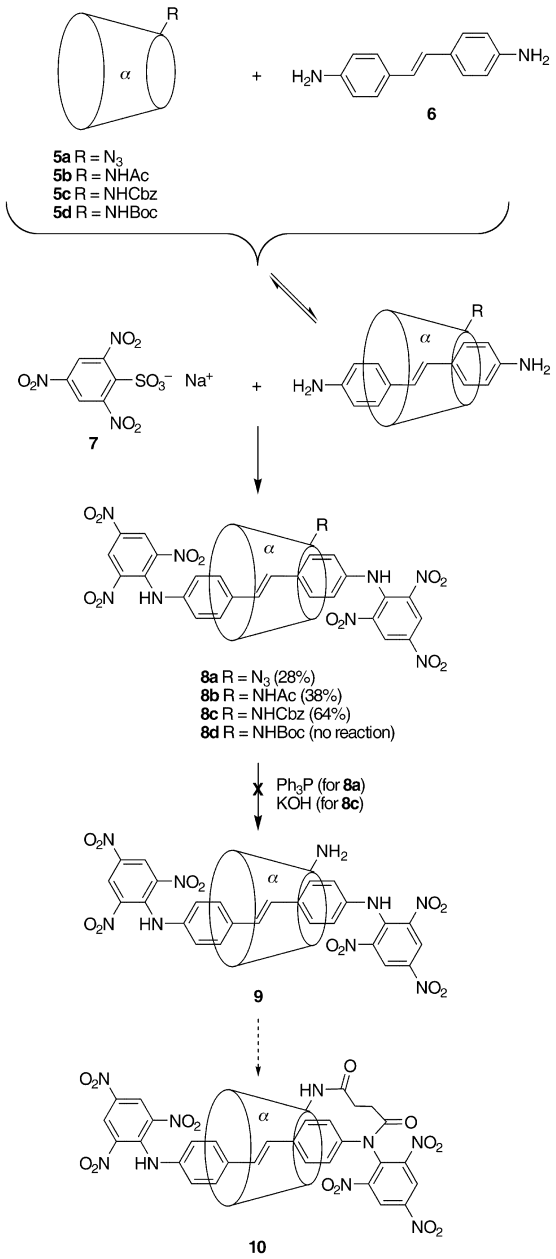
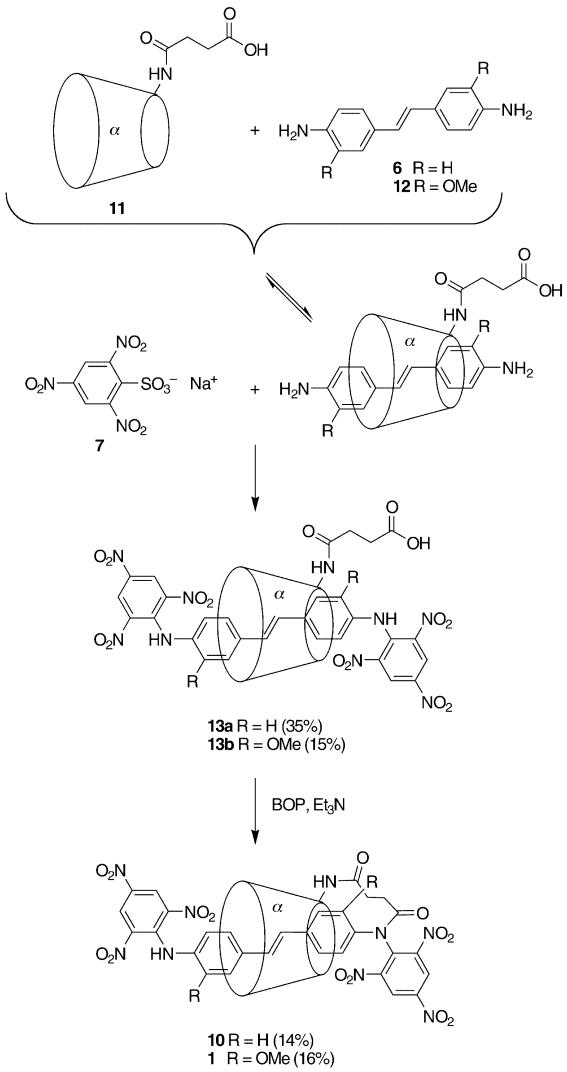
for the synthesis of the rotaxanes **2a** and **2b**, the modified cyclodextrins **5a–d** were each treated with the diaminostilbene **6** and the trinitrobenzenesulfonate **7**. The carbamate **5d** was found to be only sparingly soluble in the carbonate buffer used as the reaction solvent and, probably as a consequence, the rotaxane **8d** did not form. The rotaxanes **8a–c** were produced from the cyclodextrins **5a–c**, in yields of 28, 38 and 64%, respectively. However, all attempts to convert these to the aminocyclodextrin-based rotaxane **9** were unsuccessful.

Given these difficulties, we chose to protect the aminocyclodextrin **4** with succinic anhydride,[30] prior to rotaxane formation, with the intention of also exploiting the succinyl group as the ratchet pawl (Scheme 3). The succinamide **11** was treated with the capping reagent **7** and each of the stilbenes **6** and **12**, to give rotaxanes **13a** and **13b**, in yields of 35 and 15%, respectively. Finally, the succinyl group was attached to the axle in each of the rotaxanes **13a** and **13b**, using benzotriazol-1-yloxytris(dimethylamino) phosphonium hexafluorophosphate (BOP), to give the [1]rotaxanes[31] **10** and **1**, in yields of 14 and 16%, respectively.

The rotaxanes **2a**,**b**, **10** and **1** constitute a suitable series to investigate the effects of installing the methoxyl substitu-



Scheme 2.



Scheme 3.

ent and succinamide link, as a ratchet tooth and pawl, respectively, to restrict rotational motion. The [2]rotaxane **2a** has neither the tooth nor the pawl, the dimethoxy-stilbene derivative **2b** has only the tooth, the [1]rotaxane **10** has only the pawl, and **1** has both. The [2]rotaxane **13b**, with both the methoxyl group and the succinamide substituent, but with the latter attached only to the cyclodextrin, was also studied.

As stated above, the ^{1}H NMR spectra of the [2]rotaxanes **2a** and **2b** are simplified by the six-fold symmetry of the α-cyclodextrin moiety, reflecting its free rotation around the stilbene axle in each case. The 1D NMR spectra of **13b**, **10** and **1** are much more complex, irrespective of rotational motion, because the symmetry of the cyclodextrins is disrupted through their modification. With each cyclodextrin, the forty-two carbon-bonded hydrogens are chemically distinct and give rise to a complex resonance pattern. In order to use NOE interactions as the basis of studying conformational effects, it was first necessary to assign individual resonances to particular protons. This was achieved by using TOCSY to identify the resonances of the protons of each of the glucopyranose rings, then 2D DQF-COSY to establish the bond connections within each glucopyranose. The sequence of the glucopyranose units was then determined, using ROESY to measure NOEs between the C-1 and C-4 protons of adjacent residues. Finally HMQC was employed to identify the substituted glucopyranose.[32–34] Due to their complexity it was necessary to iteratively interpret the spectra. Following this process, resonances were assigned to the cyclodextrin protons of the rotaxanes **13b**, **10** and **1** (Figures 2–4). The assignments are summarised in Table 1, together with the corresponding data for **2a** and **2b**. It was then possible to analyze the NOEs between the stilbene and cyclodextrin components, using ROESY (Figures 5–8), having first assigned resonances to the stilbene moieties

Table 1. ^{1}H NMR chemical shifts, δ [ppm], of cyclodextrin resonances[a] in the rotaxanes **2a**,[25] **2b**,[26] **13b**, **10** and **1**.

			Cyclodextrin-C1-H			
	$C1^A$	$C1^B$	$C1^C$	$C1^D$	$C1^E$	$C1^F$
2a			4.94 (isotropic)			
2b			4.92 (isotropic)			
13b	4.92	4.97	4.91	4.92	4.94	4.97
10	4.84	4.93	4.89	4.94	4.96	5.22
1	4.87	4.98	4.89	4.94	5.00	5.29
			Cyclodextrin-C2-H			
	$C2^A$	$C2^B$	$C2^C$	$C2^D$	$C2^E$	$C2^F$
2a			3.42 (isotropic)			
2b			3.44 (isotropic)			
13b	3.48	3.49	3.44	3.47	3.44	3.47
10	3.38	3.43	3.42	3.44	3.46	3.45
1	3.34	3.47	3.42	3.44	3.50	3.48
			Cyclodextrin-C3-H			
	$C3^A$	$C3^B$	$C3^C$	$C3^D$	$C3^E$	$C3^F$
2a			3.89 (isotropic)			
2b			3.93 (isotropic)			
13b	3.86	4.02	3.91	3.91	3.86	4.04
10	3.74	3.94	3.82	3.87	3.97	3.82
1	3.72	4.06	3.92	3.86	4.08	3.94
			Cyclodextrin-C4-H			
	$C4^A$	$C4^B$	$C4^C$	$C4^D$	$C4^E$	$C4^F$
2a			3.58 (isotropic)			
2b			3.58 (isotropic)			
13b	3.42	3.54	3.62	3.58	3.58	3.64
10	3.48	3.54	3.59	3.57	3.60	3.64
1	3.48	3.60	3.62	3.57	3.62	3.68
			Cyclodextrin-C5-H			
	$C5^A$	$C5^B$	$C5^C$	$C5^D$	$C5^E$	$C5^F$
2a			3.89 (isotropic)			
2b			3.86 (isotropic)			
13b	3.92	4.00	3.83	3.83	3.84	3.99
10	3.88	3.92	3.80	3.86	3.96	3.83
1	3.88	4.03	3.84	3.80	4.06	3.86

[a] Cyclodextrin-C6 proton resonances are not shown in this table because some signals could not be assigned.

using 2D DQF-COSY and ROESY, as described previously,[25,26] and having determined the point of attachment of the stilbene to the cyclodextrin using ROESY. The TOCSY analysis depends on the six C-1 proton resonances being well differentiated, in order to take advantage of isolable magnetization transfer within each glucopyranose unit. This was not the case with **13a** so it was not included in the study.

With each of the rotaxanes **13b**, **10** and **1**, the cyclodextrin moiety rotates completely around the stilbene axle. This is apparent from the NOEs observed between the resonances of the stilbene protons and those of the C3 and C5 protons located inside the cyclodextrin annuli. For **13b** (Figure 5), NOEs are observed between each of the stilbene protons labelled A, B and C and each of the cyclodextrin $C3^{A–F}$ protons, and between each of the protons E, F and G of the stilbene and each of the $C5^{A–F}$ cyclodextrin protons. The uniform intensity of these NOEs shows not only the full rotation of the cyclodextrin around the stilbene axle, but also that rotation occurs freely on the NMR time-scale ($< 10^{-3}$ s[35]), in this case. Likewise, with **10** (Figure 6), the uniform intensity of the NOEs between stilbene protons A and B and the cyclodextrin $C3^{A–F}$ protons, as well as between protons C and D of the stilbene and the $C5^{A–F}$ protons of the cyclodextrin, gives no indication of restricted rotation. By contrast, it is clear from the NOEs that the cyclodextrin of **1** rotates completely but not freely. The full rotation is demonstrated by the observation of NOEs between stilbene proton B and each of the cyclodextrin $C3^{A–F}$ protons (Figure 7). The restriction of the rotation is obvious from the decreased intensity of the interactions of stilbene protons A and B with cyclodextrin proton $C3^A$, compared to those with cyclodextrin protons $C3^{B–F}$ (shown in Figures 7 and 8, respectively, which are portions of the ROESY spectrum printed with different threshold intensities). The restriction corresponds to passage of the adjacent methoxyl group past the succinamide link.

The restricted rotation in **1** is also apparent from the anistropy of the chemical shifts of the resonances of the cyclodextrin protons (Table 1). This is particularly the case with the signals due to the C3 and C5 protons that line the cyclodextrin annulus, which range over 0.36 and 0.26 ppm, respectively. By comparison, the corresponding signals of **13b** fall within 0.18 and 0.17 ppm, those of **10** vary by only 0.23 and 0.16 ppm, and those of **2a** and **2b** are isotropic. The significant deshielding of the signals due to the C3 and C5 protons of glucopyranose rings B and E of **1** is further evidence that rotation is not free. In addition, it indicates that the preferred conformations of the stilbene moiety within the annulus of **1** are most probably as illustrated in Figure 9. There is a similar though less substantial deshielding of the corresponding resonances of **10** but no analogous trend in the signals of **13b**. It follows that there is no conformational restriction with **13b**, but there may be some in the case of **10**. It is apparent from the extent of the deshielding and the analysis of the NOEs discussed above that the restriction is much less with **10** than with **1**.

In conclusion, the series of 2D NMR techniques discussed above has been used to analyze a range of new cyclodextrin–[2]- and –[1]rotaxanes. This has shown that while the cyclodextrin of the rotaxane **2a** rotates freely around

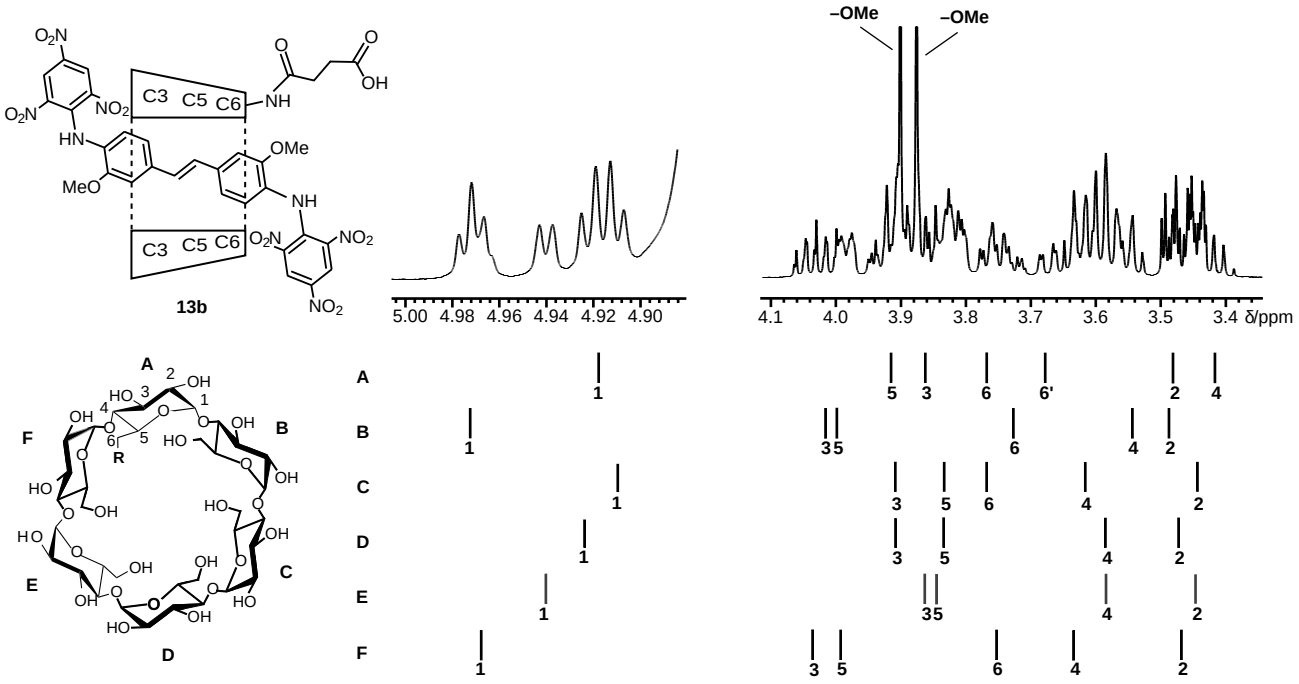


Figure 2. Resonance assignments for the cyclodextrin protons of the α-cyclodextrin [2]rotaxane **13b**, as determined using TOCSY, DQF-COSY, ROESY and HMQC NMR spectrometry, and a section of the 600 MHz ^{1}H NMR spectrum recorded in [D_4]methanol.

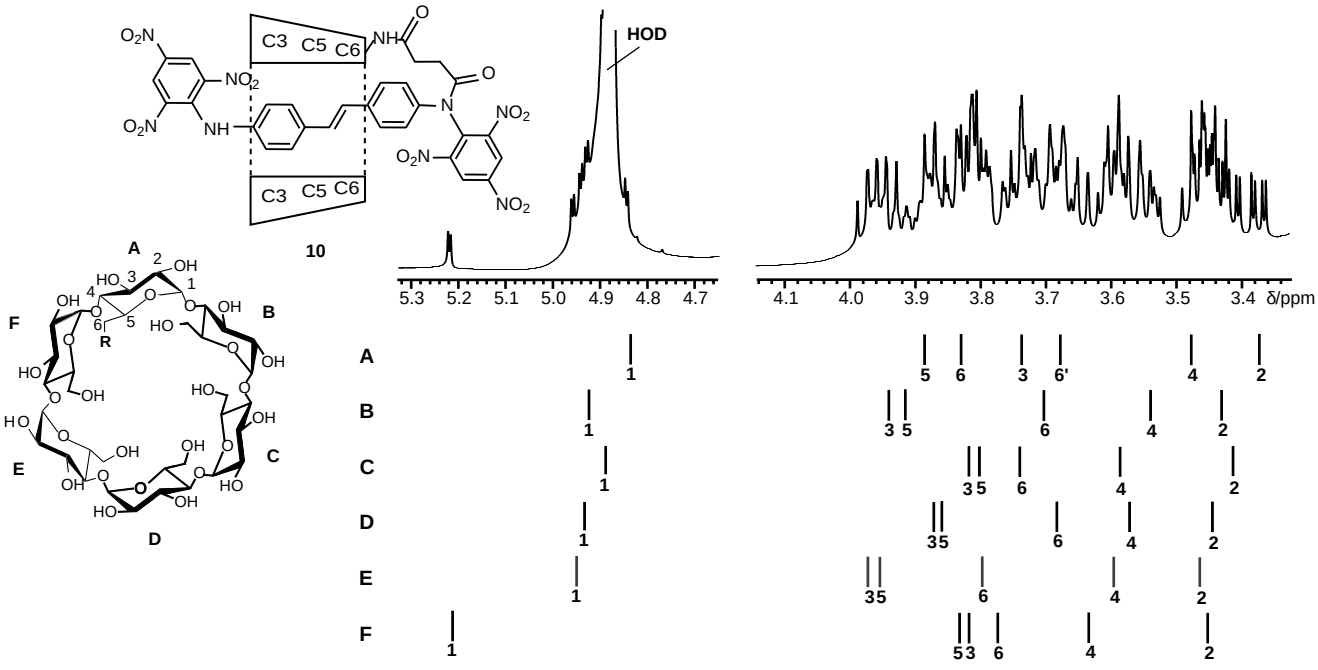


Figure 3. Resonance assignments for the cyclodextrin protons of the α-cyclodextrin [1]rotaxane **10**, as determined using TOCSY, DQF-COSY, ROESY and HMQC NMR spectrometry, and a section of the 600 MHz ^{1}H NMR spectrum recorded in [D_4]methanol.

the stilbene axle, incorporation of the methoxyl group and the succinamide link to produce **1** restricts the rotational motion on the NMR time-scale. Alone, the effect of the succinamide link of **10** is much less and the methoxyl group of **2b** has no detectable effect. This demonstrates that the methoxyl group and succinamide link of **1** interact analogously to a ratchet tooth and pawl, respectively, to restrict rotational motion.

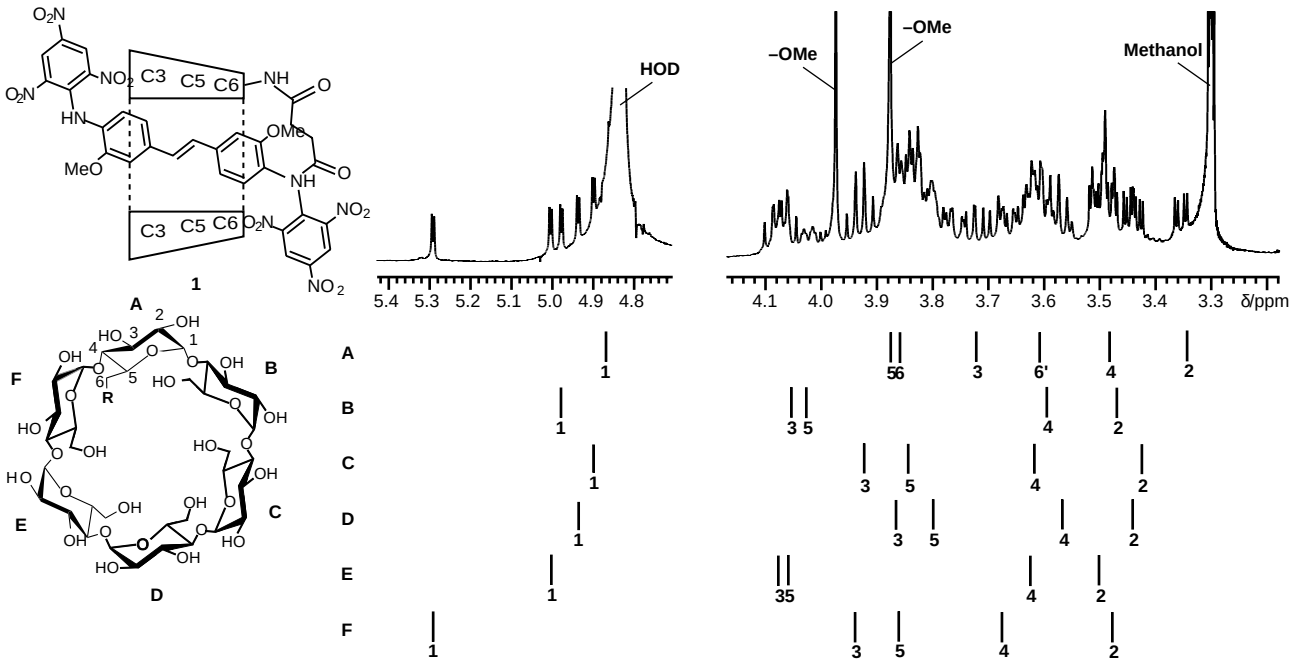


Figure 4. Resonance assignments for the cyclodextrin protons of the α-cyclodextrin [1]rotaxane **1**, as determined using TOCSY, DQF-COSY, ROESY and HMQC NMR spectrometry, and a section of the 600 MHz ^{1}H NMR spectrum recorded in [D_4]methanol.

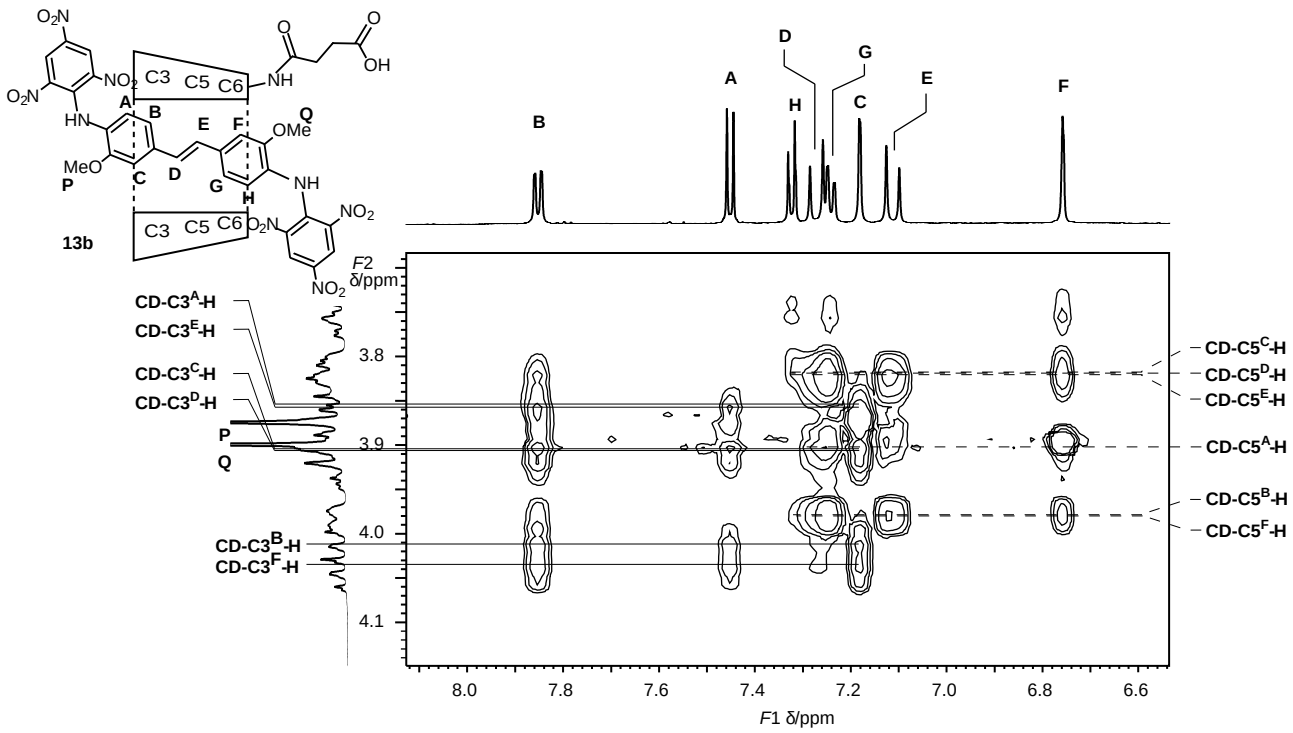


Figure 5. A section of the 600 MHz ROESY NMR spectrum of the α-cyclodextrin [2]rotaxane **13b** recorded in [D_4]methanol with a mixing time of 250 ms.

Experimental Section

General: ^{1}H NMR spectra were recorded at 500 MHz using a Varian Inova 500 spectrometer or at 600 MHz using a Varian Inova 600 spectrometer. 300 MHz ^{1}H NMR spectra were recorded using a Varian Mercury 300 spectrometer, and ^{13}C NMR spectra were recorded at 75.5 MHz using a Varian Inova 300 spectrometer. Rotating frame ^{1}H–^{1}H nuclear overhauser effect spectroscopy (ROESY) was performed with a mixing time of 250 ms. [D_4]Methanol with an isotopic purity of 99.8% and dimethyl sulfoxide ([D_6]DMSO) with an isotopic purity of 99.9% were pur-

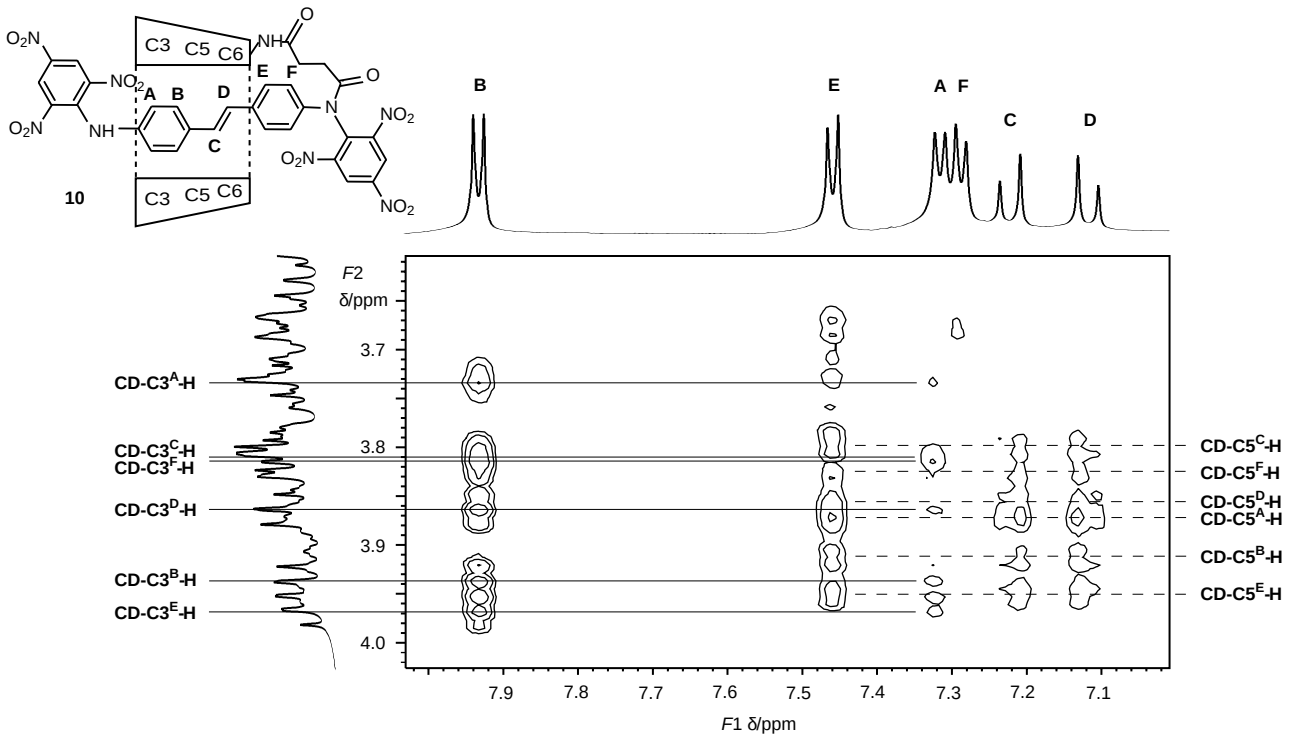


Figure 6. A section of the 600 MHz ROESY NMR spectrum of the α-cyclodextrin [1]rotaxane **10** recorded in [D_4]methanol with a mixing time of 250 ms.

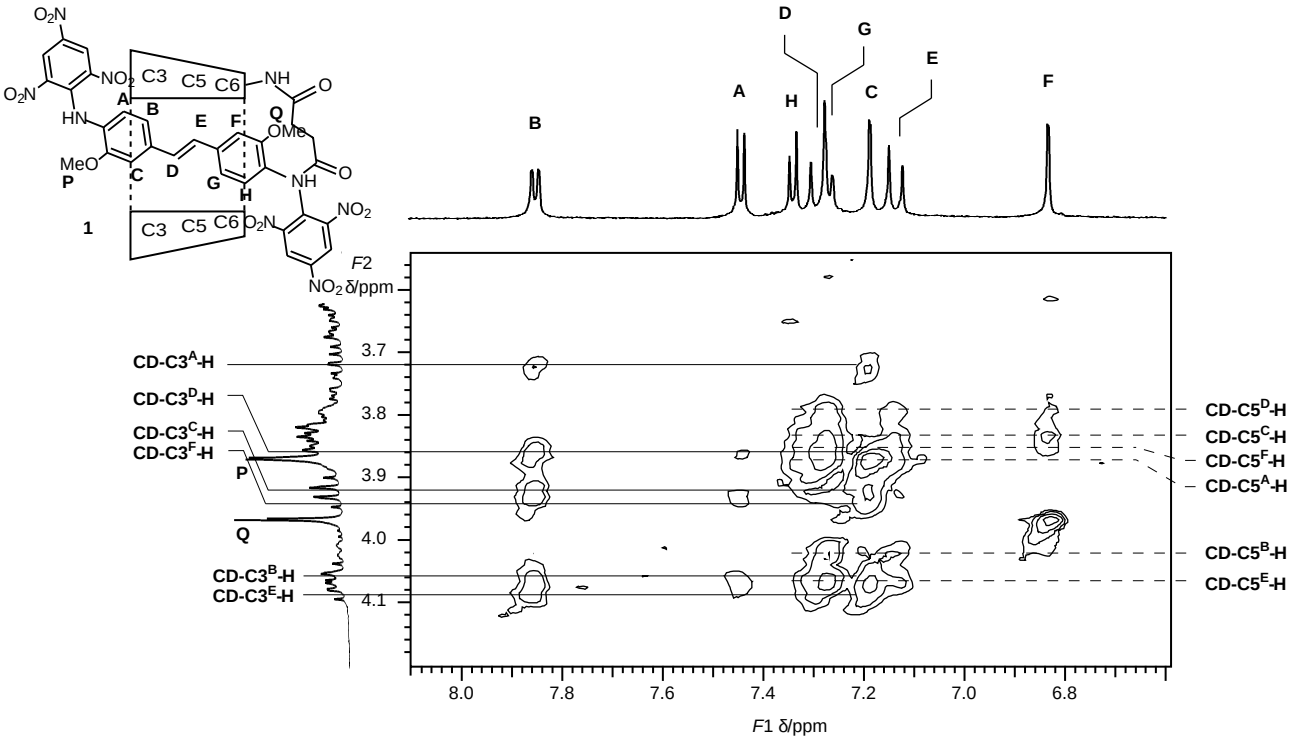


Figure 7. A section of the 600 MHz ROESY NMR spectrum of the α-cyclodextrin [1]rotaxane **1** recorded in [D_4]methanol with a mixing time of 250 ms.

chased from Cambridge Isotope Laboratories Inc., MA., and were referenced to $\delta = 3.31$ for ^{1}H and 49.15 for ^{13}C ([D_4]MeOH) and $\delta = 2.50$ for ^{1}H and 39.51 for ^{13}C ([D_6]DMSO) with respect to the resonance of Me_4Si. When deuterium oxide was used as solvent, 3-(trimethylsilyl)-3,3,2,2-tetradeuteropropionic acid sodium salt ([D_4]TSPA) was used as an external standard. Matrix-assisted laser desorption-ionization time-of-flight (MALDI-TOF) mass spectrometry was carried out with a Micromass TofSpec-2e mass spectrometer. Electrospray ionization (ESI) mass

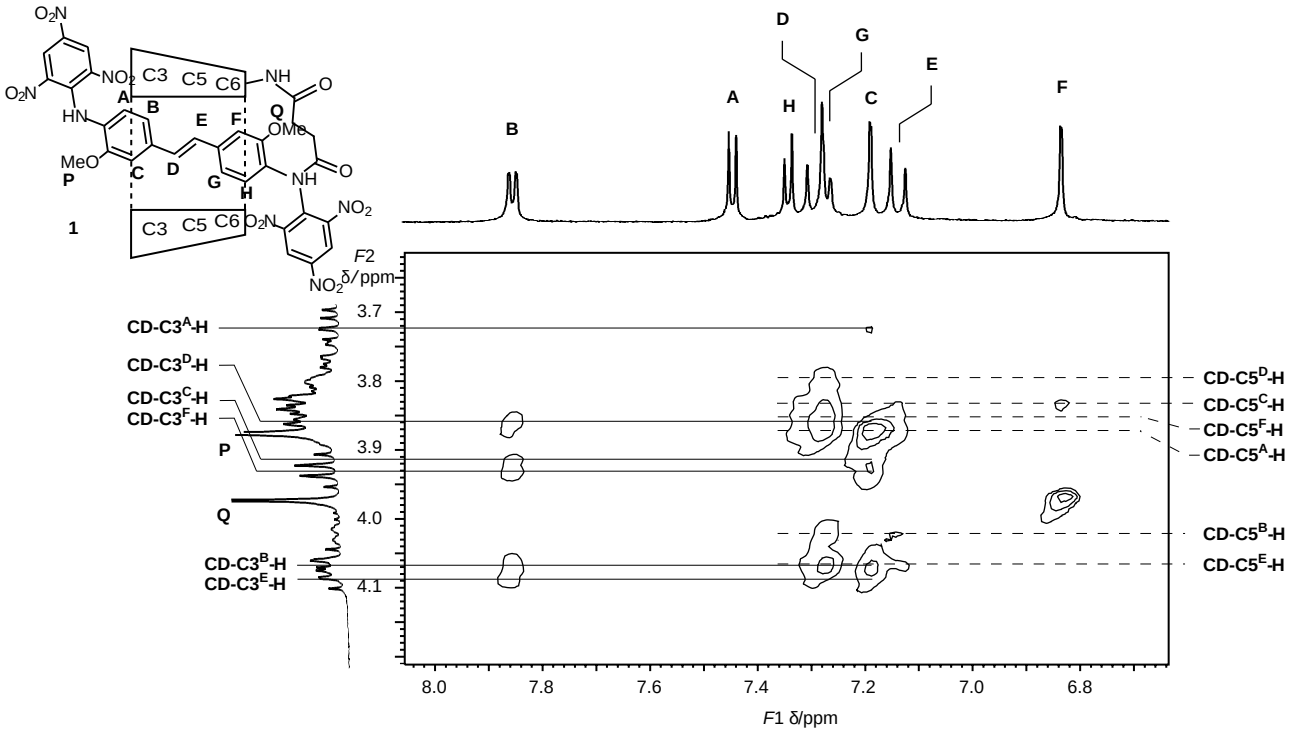


Figure 8. A section of the 600 MHz ROESY NMR spectrum of the α-cyclodextrin [1]rotaxane **1** recorded in [D_4]methanol with a mixing time of 250 ms.

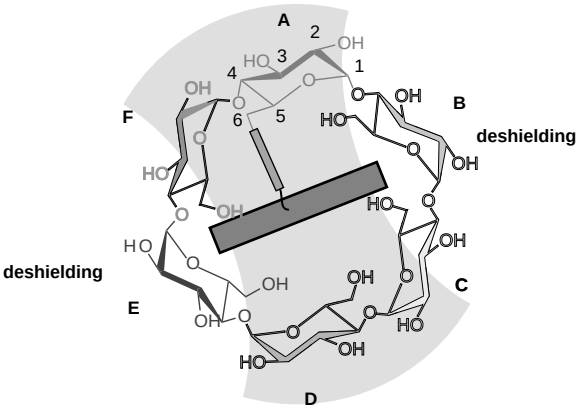


Figure 9. Preferred conformations of the stilbene moiety within the annulus of the [1]rotaxane **1**, where the 3- and 3′-methoxyl groups are directed towards glucopyranose residues B and E, respectively, or vice versa.

spectrometry was carried out with a Micromass VG Quattro II mass spectrometer. IR spectra were recorded using a Perkin-Elmer 1800 Fourier Transform Infrared Spectrometer.

Thin-layer chromatography (TLC) was performed on Kieselgel 60 F_{254} coated plates (Merck). Developed plates were visualized using UV light and/or by dipping the plate into a solution of 0.1% naphthalene-1,3-diol in ethanol/water/H_2SO_4 200:157:43, followed by heating with a heat-gun. Elemental analyses were performed by the Australian National University Microanalytical Service. Analytical and semi-preparative HPLC was carried out using a Waters Alliance Separation module 2690 with a Waters 996 photodiode array detector and a Waters 2410 Refractive Index detector. The system was controlled with a Waters Millenium operating system. A Waters Symmetry C_{18} 5 μm, 4.6×250 mm column and a YMC ODS-AQ S-5 μm, 250×4.6 mm column were used for analytical purpose. A YMC ODS-AQ S-5 μm, 250×10 mm column was used for semi-preparative purposes. Preparative HPLC was carried out using a YMC ODS-AQ 250×20 mm column or a Symmetry Prep 300×20 mm column. The solutions were loaded onto the column using a Waters 510 pump with a Waters 717 plus auto sampler, and eluents were analyzed using a Waters 486 tunable absorbance detector and a Waters 410 differential refractometer. This system was controlled using the Millipore Millennium 2010 operating system.

α-Cyclodextrin was the generous gift of Nihon Shokuhin Kako Co., Japan. It was recrystallized from water and dried in vacuo over P_2O_5 to constant weight before use. 2,4,6-Trinitrobenzene-1-sulfonic acid sodium salt dihydrate (TNBS) (**7**) was purchased from Tokyo Kasei. (*E*)-4,4′-Diaminostilbene was purchased from Aldrich Chemical Company. Diaion HP-20 resin was purchased from Supelco, PA, USA. Bio-Rex 70 Resin was obtained from Bio-Rad Laboratories, Inc, CA, USA.

[(*E*)-*N*,*N*′-Diacetyl-4,4′-bis(2,4,6-trinitrophenylamino)stilbene]-[α-cyclodextrin]-[rotaxane] (3a), [(*E*)-*N*-acetyl-4,4′-bis(2,4,6-trinitrophenylamino)stilbene]-[α-cyclodextrin]-[rotaxane] (3b) and [(*E*)-*N*′-acetyl-4,4′-bis(2,4,6-trinitrophenylamino)stilbene]-[α-cyclodextrin]-[rotaxane] (3c): Et_3N (12 μL, 1.6×10^{-4} mol) and acetyl chloride (10 μL, 2.5×10^{-4} mol) were added to a stirred solution of the [2]rotaxane **2a**[25] (64 mg, 4.0×10^{-5} mol) in dry DMF (2 mL) under a N_2 atmosphere. The mixture was stirred at room temperature for 2 h, then it was added dropwise to vigorously stirred diethyl ether (25 mL). The resulting suspension was centrifuged for 5 min at 4500 rpm and the supernatant was decanted. The remaining solid was washed with diethyl ether (25 mL) and dried under vacuum. The residue was dissolved in 25% aq. methanol (4 mL) and subjected to preparative HPLC. Fractions containing the rotaxane **3a** were concentrated under reduced pressure. The residue was lyophilized to yield a dark red powder. TLC (2-butanone/ethanol/water 9:1:1): R_f = 0.65 (relative to the solvent front), 1.45 (relative to the [2]rotaxane **2a**); ^{1}H NMR (500 MHz, [D_4]MeOH): δ = 9.10 (s, 2H; trinitrophenyl), 9.08 (s, 2H; trinitrophenyl), 8.01 (d, J = 8.5 Hz, 2H; stilbene), 7.61 (d, J = 8.0 Hz, 2H; stilbene), 7.55 (d, J = 8.5 Hz, 2H; stilbene), 7.47 (d, J = 8.0 Hz, 2H; stilbene), 7.30 (d, J_{trans} = 16.0 Hz, 1H; stilbene), 7.15 (d,

J_{trans} = 16.0 Hz, 1H; stilbene), 4.89 (unresolved, 6H; cyclodextrin-C1-H), 3.77–3.75 (m, 12H; cyclodextrin-C3 and C5-H), 3.67 (dd, J = 4.0 and 12.5 Hz, 6H; cyclodextrin-C6-H), 3.55 (apparent d, J = 12.5 Hz, 6H; cyclodextrin-C6-H′), 3.50 (apparent t, J = 9.5 Hz, 6H; cyclodextrin-C4-H), 3.44 (dd, J = 3.0 and 9.5 Hz, 6H; cyclodextrin-C2-H), 2.34 (s, 3H; acetyl), 2.28 (s, 3H; acetyl); MS (ESI, −ve): m/z: 1646 [M−COMe$^+$]; HPLC (preparative) t_R = 24.8 min [column: YMC ODS-AQ preparative; 30% aq. MeOH; flow rate: 10.0 mL min^{-1}; absorbance 422 nm].

Further fractions containing the rotaxane **3b** were concentrated and the residue was lyophilized to yield a dark red powder. TLC (2-butanone/ethanol/water 9:1:1): R_f = 0.55 (relative to the solvent front), R_f = 1.25 (relative to the [2]rotaxane **2a**); ^{1}H NMR (300 MHz, D_2O): δ = 9.18 (s, 2H; trinitrophenyl), 9.17 (s, 2H; trinitrophenyl), 7.82 (d, J = 7.7 Hz, 2H; stilbene), 7.51 (d, J = 7.7 Hz, 2H; stilbene), 7.44 (d, J = 8.2 Hz, 2H; stilbene), 7.39 (d, J = 8.2 Hz, 2H; stilbene), 7.16 (d, J_{trans} = 16.5 Hz, 1H; stilbene), 7.00 (d, J_{trans} = 16.5 Hz, 1H; stilbene), 5.00 (s, 6H; cyclodextrin-C1-H), 3.83–3.75 (m, 12H; cyclodextrin-C3 and C5-H), 3.70–3.67 (m, 6H; cyclodextrin-C6-H), 3.63–3.60 (m, 6H; cyclodextrin-C6-H′), 3.60–3.52 (m, 12H; cyclodextrin-C4 and C2-H), 2.28 (s, 3H; acetyl); MS (ESI, −ve): m/z (%): 1646 (50) [M−H$^+$], 822.5 (100) [M−2H$^+$]; HPLC (preparative): t_R = 27.0 min [column: YMC ODS-AQ preparative; 30% aq. MeOH; flow rate: 10.0 mL min^{-1}; absorbance 422 nm].

Yet further fractions containing the rotaxane **3c** were concentrated and the residue was lyophilized to yield a dark red powder. TLC (2-butanone/ethanol/water 9:1:1): R_f = 0.45 (relative to the solvent front), R_f = 1.00 (relative to the [2]rotaxane **2a**); ^{1}H NMR (500 MHz, [D$_4$]MeOH): δ = 9.11 (s, 2H; trinitrophenyl), 9.10 (s, 2H; trinitrophenyl), 8.02 (d, J = 8.5 Hz, 2H; stilbene), 7.56 (d, J = 8.5 Hz, 2H; stilbene), 7.47 (d, J = 8.5 Hz, 2H; stilbene), 7.25 (d, J = 8.5 Hz, 2H; stilbene), 7.23 (d, J_{trans} = 16.0 Hz, 1H; stilbene), 7.11 (d, J_{trans} = 16.0 Hz, 1H; stilbene), 4.89 (unresolved, 6H; cyclodextrin-C1-H), 3.90–3.75 (m, 18H; cyclodextrin-C3, C5-H and C6-H), 3.66–3.63 (m, 6H; cyclodextrin-C6-H′), 3.55 (apparent t, J = 8.5 Hz, 6H; cyclodextrin-C4-H), 3.46 (dd, J = 3.0 and 9.5 Hz, 6H; cyclodextrin-C2-H), 2.34 (s, 3H; acetyl); MS (ESI, −ve): m/z (%): 1646 (100) [M−H$^+$], 801.5 (100) [M−H−COMe$^+$]; HPLC (preparative): t_R = 36.6 min [column: YMC ODS-AQ preparative; 30% aq. MeOH; flow rate: 10.0 mL min^{-1}; absorbance 422 nm].

6^A-Acetamido-6^A-deoxy-α-cyclodextrin (5b): Acetic anhydride (11.3 μL, 1.2×10^{-4} mol) and Et$_3$N (16.7 μL, 1.2×10^{-4} mol) were added to a solution of the aminocyclodextrin **4** (100 mg, 1.0×10^{-4} mol) dissolved in dry DMF (5 mL) and the mixture was stirred for 10 h at room temperature, then it was concentrated under reduced pressure until the volume of the mixture was halved. The residue was added dropwise to acetone (15 mL). The resultant precipitate was collected by centrifugation and dried. The crude product was dissolved in water (50 mL) and the solution was applied to a Bio-Rex 70 column to remove unreacted amine **4**. The eluent was concentrated and the residue was lyophilized to give the acetamide **5b** as a colorless powder (87 mg, 86%). TLC (isopropanol/ethanol/water/acetic acid 5:4:3:2): R_f = 0.60 (relative to the solvent front), R_f = 1.9 (relative to the amine **4**); ^{1}H NMR (300 MHz, D_2O): δ = 5.00 (s, 6H; cyclodextrin-C1-H), 3.90–3.20 (m, 36H; cyclodextrin-C2 to -C6-H), 1.92 (s, 3H; acetyl); MS (ESI, +ve): m/z (%): 1014 (100) [M^+], 1037 (29) [M+Na$^+$]. These data are consistent with literature data.[30]

6^A-Benzyloxycarbonylamino-6^A-deoxy-α-cyclodextrin (5c): Amine **4** (200 mg, 2.0×10^{-4} mol) was treated with a solution containing benzyl chloroformate (256 mg, 1.5×10^{-3} mol) and NaHCO$_3$ (154 mg, 1.83×10^{-3} mol) in water (6 mL). After 1 h, the mixture was washed with diethyl ether and concentrated under reduced pressure. The residue was dissolved in water (50 mL) and the solution was applied to a Diaion HP-20 column (240×10 mm). The column was eluted with a water–methanol gradient. The carbamate **5c** was obtained when the column was eluted with 30–40% methanol. These fractions were concentrated under reduced pressure and the residue was lyophilized to give a colorless powder (130 mg, 59%). TLC (isopropanol/ethanol/water/acetic acid 5:4:3:2): R_f = 0.65 (relative to the solvent front), R_f = 2.3 (relative to the amine **4**); ^{1}H NMR (300 MHz, D_2O): δ = 7.58 (m, 2H; ArH), 7.41 (m, 2H; ArH), 7.25 (m, 1H; ArH), 5.00–4.60 (m, 8H; cyclodextrin-C1-H and benzyl CH$_2$), 4.10–3.10 (m, 36H; cyclodextrin-C2 to C6-H); ^{13}C NMR (75.5 MHz, D_2O): δ = 138.9, 131.3, 130.9, 130.3, 104.4, 104.1, 103.9, 102.9, 102.6, 85.7, 83.6, 83.0, 76.7, 75.9, 75.5, 75.2, 74.2, 73.1, 72.6, 69.4, 62.8, 62.5, 44.4; MS (MALDI-TOF): m/z: 1145 [M+K$^+$].

6^A-*tert*-Butoxycarbonylamino-6^A-deoxy-α-cyclodextrin (5d): Amine **4** (500 mg, 5.1×10^{-4} mol) and Et$_3$N (78 μL, 5.6×10^{-4} mol) were dissolved in DMF (10 mL). Boc$_2$O (560 mg, 2.57×10^{-3} mol) was added and the mixture was stirred for one day at room temperature, then it was concentrated under reduced pressure. The residual solid was washed extensively with water and the residue was lyophilized to yield the title compound **5d** (290 mg, 53%) as a colorless powder. TLC (*n*-butanol/ethanol/water 5:4:3): R_f = 0.60 (relative to the solvent front), R_f = 1.45 (relative to the amine **4**); ^{1}H NMR (500 MHz, [D$_6$]DMSO]): δ = 6.80 (s, 1H; NH), 5.64–5.36 (m, 11H; cyclodextrin-C2 and -C3^{B-F}-OH), 5.25 (s, 1H; cyclodextrin-C3^A-OH), 4.83–4.75 (m, 6H; cyclodextrin-C1-H), 4.57–4.29 (m, 5H; cyclodextrin-C6-OH), 3.90–3.69 (m, 6H; cyclodextrin-C3-H), 3.69–3.26 (m, 28H; cyclodextrin-C2, C4, C5-H and C6^{B-F}-H and H′), 3.16–3.09 (m, 1H; cyclodextrin-C6^A-H), 2.76–2.77 (m, 1H; cyclodextrin-C6^A-H′), 1.29 (s, 9H; CH$_3$); ^{13}C NMR (75.5 MHz, [D$_6$]DMSO): δ = 160.9 (C=O), 107.6–107.5 (cyclodextrin-C1^{B-F}) 107.0 (cyclodextrin-C1^A), 89.75–86.95 (cyclodextrin-C4), 82.8 [C(CH$_3$)$_3$], 78.9–78.4 (cyclodextrin-C3), 77.7–77.3 (cyclodextrin-C2 and C5), 64.9 (cyclodextrin-C6), 33.6 (CH$_3$); MS (ESI, +ve): m/z (%): 1071 (75) [M^+], 1094 (30) [M+Na$^+$], 972 (100); elemental analysis calcd (%) for $C_{41}H_{69}NO_{31}\cdot3H_2O$: C 43.73, H 6.71, N 1.24; found C 44.11, H 6.43, N 1.17.

[(*E*)-4,4′-Bis(2,4,6-trinitrophenylamino)stilbene]-[6^A-azido-6^A-deoxy-α-cyclodextrin]-[rotaxane] (8a): Stilbene **6** (21 mg, 1.0×10^{-4} mol) was added to a solution of the azide **5a** (100 mg, 1.0×10^{-4} mol) in 0.2 mol L^{-1} carbonate buffer (pH 10, 50 mL) and the mixture was stirred for 2 h. TNBS **7** (140 mg, 4.0×10^{-4} mol) was then added and the mixture was stirred for 12 h. The resulting dark red solution was washed with ethyl acetate (5×25 mL), then it was concentrated under reduced pressure. The residue was dissolved in water (50 mL) and the solution was applied to a Diaion HP-20 column (240×10 mm). The column was flushed with water (200 mL), then eluted with a water–methanol gradient. Rotaxane **8a** was obtained when the column was eluted with 50–60% methanol. These fractions were concentrated under reduced pressure and the residue was lyophilized to give a red powder (46 mg, 28%). TLC (*n*-butanol/ethanol/water 5:4:3): R_f = 0.80 (relative to the solvent front), R_f = 1.5 (relative to the azide **5a**); ^{1}H NMR (500 MHz, [D$_4$]MeOH): δ = 9.13 (s, 2H; trinitrophenyl), 9.10 (s, 2H; trinitrophenyl), 7.94 (d, J = 8.3 Hz, 2H; stilbene), 7.43 (d, J = 8.3 Hz, 2H; stilbene), 7.34 (d, J = 8.3 Hz, 2H; stilbene), 7.28 (d, J = 8.3 Hz, 2H; stilbene), 7.22 (d, J_{trans} = 16.1 Hz, 1H; stilbene), 7.12 (d, J_{trans} = 16.1 Hz, 1H; stilbene), 4.99–4.96 (m, 6H; cyclodextrin-C1-H), 4.03–3.98 (m, 4H; cyclodextrin-C3-H), 3.92–3.42 (m, 35H; cyclodextrin-C2, C3, C4, C5-H and C6-H and C6^{B-F}-H′), 3.36 (dd, J = 3.9 and 13.7 Hz, 1H; cyclodextrin-C6^A-H′); ^{13}C NMR (75.5 MHz, [D$_6$]DMSO): δ = 140.1, 139.4, 139.2, 138.6, 138.2, 138.0, 136.6, 136.1, 135.1, 133.6 (all quaternary), 128.6 (stilbene, two coincident resonances), 127.6 (stilbene, two coincident resonances), 127.1 (trinitrophenyl CH), 126.8 (trinitrophenyl CH), 121.4 (stilbene, two coincident resonances), 103.3, 103.0, 102.6, 102.3, 83.3, 82.6, 82.4, 82.2, 82.0, 74.1, 73.8, 73.5, 73.0, 72.9, 72.5, 72.2, 70.5, 60.0, 59.5, 50.9; MS (ESI, +ve): m/z: 1652 [M+Na$^+$]; elemental analysis calcd (%) for $C_{62}H_{75}N_{11}O_{41}\cdot7H_2O$: C 42.40, H 5.11, N 8.77; found C 42.59, H 4.92, N 8.73.

[(*E*)-4,4′-Bis(2,4,6-trinitrophenylamino)stilbene]-[6^A-acetamido-6^A-deoxy-α-cyclodextrin]-[rotaxane] (8b): Stilbene **6** (21 mg, 1.0×10^{-4} mol) was added to a stirred solution of the cyclodextrin **5b** (100 mg, 1.0×10^{-4} mol) in 0.2 mol L^{-1} carbonate buffer (pH 10, 10 mL), and the mixture was stirred for 2 h at room temperature. TNBS **7** (77 mg, 2.2×10^{-4} mol) was then added and the mixture was stirred at room temperature for 12 h, before it was neutralized through the dropwise addition of 1 mol L^{-1} HCl. The mixture was washed with ethyl acetate (5×25 mL) and concentrated under reduced pressure. The residue was dissolved in water (200 mL) and the solution was applied to a Diaion HP-20 column (310×25 mm), which was eluted with a water–methanol gradient. The rotaxane **8b** was obtained when the column was eluted with 40–70% methanol. These fractions were concentrated under reduced pressure and the residue was lyophilized to give a red powder (62 mg, 38%). TLC (*n*-butanol/ethanol/water 5:4:3): R_f = 0.60 (relative to the solvent front); ^{1}H NMR (500 MHz, [D$_4$]MeOH): δ = 9.15 (s, 2H; trinitrophenyl), 9.10 (s, 2H; trinitrophenyl), 7.95 (d, J = 8.3 Hz, 2H; stilbene), 7.40 (d, J = 8.3 Hz, 2H; stilbene), 7.35 (d, J = 8.3 Hz, 2H; stilbene), 7.27 (d, J = 8.3 Hz, 2H; stilbene), 7.23 (d, J_{trans} = 16.6 Hz, 1H; stilbene), 7.12 (d, J_{trans} = 16.1 Hz, 1H; stilbene), 4.99–4.92 (m, 6H; cyclodextrin-C1-H), 4.03–3.35 (m, 36H;

cyclodextrin), 1.94 (s, 3H; acetyl); ^{13}C NMR (75.5 MHz, [D$_4$]MeOH): δ = 172.4 (C=O), 139.4, 138.7, 138.4, 136.5, 135.0, 133.9 (all quaternary), 128.9, 128.7, 128.4, 127.3, 127.1, (stilbene), 126.9 (trinitrophenyl), 121.9, 121.8 (stilbene), 103.0, 102.8, 83.6, 82.3, 82.0, 73.9, 73.8, 73.5, 73.1, 73.0, 72.8, 72.6, 72.4, 70.9, 60.5, 60.1, 39.5, 21.4 (acetyl); MS (ESI, +ve): *m/z*: 1668 [*M*+Na$^+$]; elemental analysis calcd (%) for $C_{64}H_{79}N_9O_{42}\cdot 7H_2O$: C 43.37, H 5.29, N 7.11; found C 43.45, H 5.11, N 6.81.

[(*E*)-4,4′-Bis(2,4,6-trinitrophenylamino)stilbene]-[6^A-benzyloxycarbonylamino-6^A-deoxy-α-cyclodextrin]-[rotaxane] (8c): Stilbene **6** (9.5 mg, 4.52×10^{-5} mol) was added to a stirred solution of the cyclodextrin **5c** (50 mg, 4.52×10^{-5} mol) in 0.2 mol L^{-1} carbonate buffer (pH 10, 25 mL), and the mixture was stirred for 2 h at room temperature. TNBS **7** (35 mg, 1.0×10^{-4} mol) was then added and the mixture was stirred at room temperature for 12 h, before it was neutralized through the dropwise addition of 1 mol L^{-1} HCl and concentrated under reduced pressure. The residue was dissolved in 50% aq. MeCN (2 mL) and the solution was subjected to preparative HPLC. Fractions containing the rotaxane **8c** were concentrated under reduced pressure and the residue was lyophilized to yield a dark red powder (50.7 mg, 64%). ^{1}H NMR (600 MHz, [D$_4$]MeOH): δ = 9.12 (s, 2H; trinitrophenyl), 9.03 (s, 2H; trinitrophenyl), 7.93 (d, *J* = 8.6 Hz, 2H; stilbene), 7.41 (d, *J* = 8.4 Hz, 2H; stilbene), 7.33 (d, *J* = 8.6 Hz, 2H; stilbene), 7.30–7.25 (m, 5H; Cbz), 7.24 (d, *J* = unresolved, 2H; stilbene), 7.11 (d, J_{trans} = 16.1 Hz, 1H; stilbene), 6.99 (d, J_{trans} = 16.1 Hz, 1H; stilbene), 5.08–5.01 (m, 2H; benzyl), 4.95–4.89 (m, 6H; cyclodextrin-C1-H), 3.94–3.35 (m, 36H; cyclodextrin); MS (MALDI-TOF): *m/z*: 1762 [*M*+Na$^+$]; HPLC (preparative) t_R = 4.6 min [column: Symmetry Prep C18; 50% aq. MeCN; flow rate: 10 mL min^{-1}].

6^A-(3-Carboxypropionamido)-6^A-deoxy-α-cyclodextrin (11): Succinic anhydride (20 mg, 0.20×10^{-3} mol) was added to a solution of the aminocyclodextrin **4** (200 mg, 0.20×10^{-3} mol) dissolved in dry DMF (10 mL) and the mixture was stirred for 10 h at room temperature, before it was added dropwise to acetone (75 mL). The resultant precipitate was collected by centrifugation and resuspended in acetone (20 mL). The solid was collected by centrifugation and lyophilized to give a colorless powder (214 mg, quantitative). TLC (*n*-butanol/ethanol/water 5:4:3): R_f = 0.25 (relative to the solvent front); ^{1}H NMR (500 MHz, D$_2$O): δ = 5.03 (s, 6H; cyclodextrin-C1-H), 3.98–3.61 (m, 35H; cyclodextrin-C2 to C6-H), 3.46 (m, 1H; cyclodextrin-C6^A-H), 2.51–2.42 (m, 4H; succinyl); MS (MALDI-TOF): *m/z*: 1094 [*M*+Na$^+$]. These ^{1}H NMR spectral data are consistent with literature values.[30]

[(*E*)-4,4′-Bis(2,4,6-trinitrophenylamino)stilbene]-[6^A-(3-carboxypropionamido)-6^A-deoxy-α-cyclodextrin]-[rotaxane] (13a): Stilbene **6** (107 mg, 5.1×10^{-4} mol) was added to a stirred solution of the cyclodextrin **11** (185 mg, 1.7×10^{-4} mol) in 0.2 mol L^{-1} carbonate buffer (pH 10, 5 mL), and the suspension was stirred for 2 h at 25 °C. TNBS **7** (358 mg, 1.1×10^{-3} mol) was then added and the mixture was stirred at 25 °C for 12 h, before it was neutralized through the dropwise addition of 1 mol L^{-1} HCl. The resulting solution was added dropwise to acetone (75 mL) and the suspension was centrifuged for 5 min at 4500 rpm. The supernatant was decanted and the remaining solid was dried under vacuum. The residue was dissolved in water (10 mL) and the solution was applied to a Diaion HP-20 column (150×15 mm), which was eluted with a water–methanol gradient. The rotaxane **13a** was obtained when the column was eluted with 30–50% methanol. These fractions were concentrated under reduced pressure and the residue was lyophilized to give a red powder (100 mg, 35%). TLC (*n*-butanol/ethanol/water 5:4:3): R_f = 0.65 (relative to the solvent front), R_f = 2.65 (relative to the cyclodextrin **11**); ^{1}H NMR (500 MHz, D$_2$O): δ = 9.23 (s, 2H; trinitrophenyl), 9.22 (s, 2H; trinitrophenyl), 7.86 (d, *J* = 8.3 Hz, 2H; stilbene), 7.42 (d, *J* = 8.3 Hz, 2H; stilbene), 7.32 (s, 4H; stilbene), 7.11 (d, J_{trans} = 16.5 Hz, 1H; stilbene), 6.99 (d, J_{trans} = 16.5 Hz, 1H; stilbene), 5.10 (d, *J* = 3.4 Hz, 1H; cyclodextrin-C1^F-H), 5.06–5.05 (m, 4H; cyclodextrin-C1^{B-E}-H), 5.04 (d, *J* = 4.4 Hz, 1H; cyclodextrin-C1^A-H), 4.1–3.7 (m, 12H; cyclodextrin-C3 and C5-H), 3.9–3.4 (m, 12H; cyclodextrin-C6-H), 3.7–3.4 (m, 6H; cyclodextrin-C4-H), 3.6–3.4 (m, 6H; cyclodextrin-C2-H), 2.53–2.34 (m, 4H; succinyl); ^{13}C NMR (75.5 MHz, [D$_4$]MeOH): δ = 175.0 (C=O), 173.6 (C=O), 139.4, 139.2, 138.8, 138.7, 138.4, 136.5, 136.1, 135.0, 133.9 (all quaternary), 128.7 (stilbene), 128.4 (stilbene), 127.4 (stilbene, two coincident resonances), 127.0 (trinitrophenyl, two coincident resonances), 121.9 (stilbene), 121.8 (stilbene), 103.0, 102.8, 102.6, 83.2, 82.4, 82.2, 82.1, 82.0, 81.9, 74.0, 73.8, 73.6, 73.1, 73.0, 72.8, 72.7, 72.6, 72.5, 71.0, 60.8, 60.5, 60.4, 60.2, 39.3, 30.3, 29.1 (succinyl); IR (KBr pellet): $\tilde{\nu}$ = 3412, 2929, 1621, 1594, 1517, 1335, 1291, 1150, 1078, 1030, 933, 723, 576 cm^{-1}; MS (MALDI-TOF): *m/z*: 1727 [*M*+Na$^+$]; elemental analysis calcd (%) for $C_{66}H_{81}N_9O_{44}\cdot 9H_2O$: C 42.47, H 5.35, N 6.75; found C 42.55, H 5.06, N 6.69; HPLC (analytical): t_R = 2.4 min [column: Symmetry C$_{18}$; 46% aq. MeCN containing 0.1% TFA *v/v*; flow rate: 1.3 mL min^{-1}]; (preparative): t_R = 4.1 min [column: YMC ODS-AQ; 45% aq. MeCN containing 0.1% TFA *v/v*; flow rate: 3 mL min^{-1}].

[(*E*)-3,3′-Dimethoxy-4,4′-bis(2,4,6-trinitrophenylamino)stilbene]-[6^A-(3-carboxypropionamido)-6^A-deoxy-α-cyclodextrin]-[rotaxane] (13b): Stilbene **12** (44 mg, 1.63×10^{-4} mol) was added to a stirred solution of the cyclodextrin **11** (175 mg, 1.63×10^{-4} mol) in 0.2 mol L^{-1} carbonate buffer (pH 10, 70 mL), and the suspension was stirred for 2 h at room temperature. TNBS **7** (500 mg, 1.42×10^{-3} mol) was then added and the mixture was stirred at room temperature for 48 h, before it was neutralized through the dropwise addition of 1 mol L^{-1} HCl. The resulting dark red solution was washed with ethyl acetate (4×50 mL), then it was concentrated under reduced pressure. The residue was dissolved in water (100 mL) and the solution was applied to a Diaion HP-20 column (310×25 mm), which was flushed with water (800 mL) and then 10% aqueous methanol (400 mL). The column was then eluted with a water–methanol gradient. Rotaxane **13b** was obtained when the column was eluted with 40–60% methanol. These fractions were concentrated under reduced pressure and the residue was lyophilized to give a red powder (43 mg, 15%). TLC (*n*-butanol/ethanol/water 5:4:3): R_f = 0.75 (relative to the solvent front), R_f = 1.30 (relative to the cyclodextrin **11**); ^{1}H NMR (600 MHz, [D$_4$]MeOH): δ = 9.10 (s, 2H; trinitrophenyl), 9.09 (s, 2H; trinitrophenyl), 7.86 (d, *J* = 8.5 Hz, 1H; stilbene), 7.45 (d, *J* = 8.5 Hz, 1H; stilbene), 7.33 (d, *J* = 8.5 Hz, 1H; stilbene), 7.28 (d, J_{trans} = 16.0 Hz, 1H; stilbene), 7.25 (d, *J* = 8.5 Hz, 1H; stilbene), 7.19 (s, 1H; stilbene), 7.12 (d, J_{trans} = 16.0 Hz, 1H; stilbene), 6.76 (s, 1H; stilbene), 5.0–3.4 (m, 42H; cyclodextrin protons, for assignments see Figure 2), 3.90 (s, 3H; OMe), 3.88 (s, 3H; OMe), 2.64–2.35 (m, 4H; succinyl); ^{13}C NMR (75.5 MHz, [D$_4$]MeOH): δ = 175.0 (C=O), 173.7 (C=O), 152.6, 152.5, 138.9, 138.7, 138.5, 138.3, 136.6, 135.8, 135.4, 135.3 (all quaternary), 129.7 (stilbene), 128.2 (stilbene), 126.7 (quaternary), 126.1 (trinitrophenyl, two coincident resonances), 125.9 (quaternary), 124.7 (stilbene), 123.1 (stilbene), 118.8 (stilbene), 116.6 (stilbene), 112.4 stilbene), 112.3 (stilbene), 102.8, 102.5, 82.9, 82.5, 82.1, 82.0, 81.9, 73.9, 73.8, 73.6, 73.0, 73.0, 72.7, 72.6, 72.5, 70.9, 60.6, 60.4, 56.2, 56.1, 26.0, 23.0 (succinyl); IR (KBr, pellet): $\tilde{\nu}$ = 3384, 2932, 1673, 1619, 1593, 1516, 1418, 1335, 1293, 1202, 1148, 1077, 1029, 946, 850, 800, 723, 578, 523 cm^{-1}; MS (MALDI-TOF): *m/z*: 1787 [*M*+Na$^+$]; HPLC (analytical): t_R = 4.2 min [column: Symmetry C$_{18}$; 30% aq. MeCN; flow rate: 1 mL min^{-1}].

[*N*′-(6^A-Deoxy-α-cyclodextrin-6^A-yl(*N*-3-amidopropionoyl))]-[(*E*)-4,4′-bis(2,4,6-trinitrophenylamino)stilbene]-[rotaxane] (10): BOP (25 mg, 5.6×10^{-5} mol) and triethylamine (7.8 μL, 5.6×10^{-4} mol) were added to a stirred solution of the rotaxane **13a** (50 mg, 4.7×10^{-5} mol) in dry DMF (2 mL), and the mixture was stirred under a nitrogen atmosphere at room temperature. After 6 h, an additional portion of BOP (12.5 mg, 2.8×10^{-5} mol) was added and the mixture was stirred overnight. The resulting solution was added dropwise to acetone (75 mL) and the suspension was centrifuged for 5 min at 4500 rpm. The supernatant was decanted and the remaining solid was dried under vacuum. The residue was dissolved in 25% aq. MeCN (1 mL), and the solution was subjected to preparative HPLC. Fractions containing the rotaxane **10** were concentrated under reduced pressure and the residue was lyophilized to yield a dark red powder (11 mg, 14%). TLC (*n*-butanol/ethanol/water 5:4:3): R_f = 0.70 (relative to the solvent front), R_f = 1.15 (relative to the rotaxane **13a**); ^{1}H NMR (600 MHz, [D$_4$]MeOH): δ = 9.11 (s, 2H; trinitrophenyl), 9.07 (s, 2H; trinitrophenyl), 7.93 (d, *J* = 8.4 Hz, 2H; stilbene), 7.46 (d, *J* = 8.4 Hz, 2H; stilbene), 7.33 (d, *J* = 8.4 Hz, 2H; stilbene), 7.29 (d, *J* = 8.4 Hz, 2H; stilbene), 7.22 (d, J_{trans} = 16.4 Hz, 1H; stilbene), 7.12 (d, J_{trans} = 16.4 Hz, 1H; stilbene), 5.22–3.35 (m, 422H; cyclodextrin protons, for assignments see Figure 3), 2.66 (s, 4H; succinyl); ^{13}C NMR (75.5 MHz, [D$_4$]MeOH): δ = 178.9 (C=O, amide, two coincident resonances), 139.4, 139.2, 138.7, 138.5, 136.5, 136.0, 135.1, 134.0 (all quaternary), 128.8 (stilbene), 128.4 (stilbene), 127.6 (stilbene), 127.6 (stilbene), 127.0 (trinitrophenyl, two coincident resonances), 121.9 (stilbene), 121.8 (stilbene), 103.1, 102.9, 102.4, 102.1, 84.7, 82.4, 82.3, 82.0, 81.9, 73.9, 73.6, 72.8, 72.5, 72.3, 69.8, 60.6, 60.2, 37.8, 27.8 (succinyl); IR (KBr pellet): $\tilde{\nu}$

= 3391, 2931, 1698, 1621, 1594, 1537, 1516, 1426, 1404, 1335, 1291, 1173, 1149, 1078, 1030, 946, 932, 851, 723, 704, 576, 538 cm^{-1}; MS (MALDI-TOF): *m*/*z*: 1709 [*M*+Na^+]; HPLC (analytical): t_R = 5.5 min, 1.3 (relative to the rotaxane **13a**) [column: Symmetry C_{18}; 25% aq. MeCN containing 0.1% TFA *v*/*v*; flow rate: 1 mL min^{-1}]; (preparative) t_R = 7.3 min [column: Symmetry Prep C18; 25% aq. MeCN containing 0.1% TFA *v*/*v*; flow rate: 10 mL min^{-1}].

[*N*′-(6^A-Deoxy-α-cyclodextrin-6^A-yl(*N*-3-amidopropionoyl))]-[(*E*)-3,3′-dimethoxy-4,4′-bis(2,4,6-trinitrophenylamino)stilbene]-[rotaxane] (1): BOP (4.3 mg, 10.2×10^{-6} mol) and Et_3N (5.0 μL, 3.5×10^{-5} mol) were added to a stirred solution of the rotaxane **13b** (15 mg, 8.5×10^{-6} mol) in dry DMF (1.0 mL). The mixture was stirred under a nitrogen atmosphere for 48 h at room temperature. The solvent was then removed under reduced pressure and the residual solid was dissolved in 25% aq. MeCN (1 mL). The resultant solution was subjected to preparative HPLC. Fractions containing the rotaxane **1** were concentrated under reduced pressure and the residue was lyophilized to yield a dark red powder (2.4 mg, 16%). TLC (*n*-butanol/ethanol/water 5:4:3): R_f = 0.75 (relative to the solvent front), R_f = 1.10 (relative to the rotaxane **13b**); ^{1}H NMR (600 MHz, [D_4]MeOH): δ = 9.10 (s, 2H; trinitrophenyl), 9.09 (s, 2H; trinitrophenyl), 7.85 (d, *J* = 8.5 Hz, 1H; stilbene), 7.44 (d, *J* = 8.5 Hz, 1H; stilbene), 7.34 (d, *J* = 8.5 Hz, 1H; stilbene), 7.29 (d, J_{trans} = 16.3 Hz, 1H; stilbene), 7.27 (d, *J* = 8.5 Hz, 1H; stilbene), 7.19 (s, 1H; stilbene), 7.13 (d, J_{trans} = 16.3 Hz, 1H; stilbene), 6.83 (s, 1H; stilbene), 5.29–3.55 (m, 42H; cyclodextrin protons, for assignments see Figure 4), 3.98 (s, 3H; OMe), 3.88 (s, 3H; OMe), 2.66–2.62 (m, 4H; succinyl); MS (MALDI-TOF): *m*/*z* 1769 [*M*+Na^+]; HPLC (analytical): t_R = 7.4 min [column: Symmetry C_{18}; 25% aq. MeCN containing 0.1% TFA *v*/*v*; flow rate: 1 mL min^{-1}]; (preparative): t_R = 8.5 min [column: Symmetry Prep C18; 30% aq. MeCN containing 0.1% TFA *v*/*v*; flow rate: 10 mL min^{-1}].

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