# High-Yield Synthesis of Ester, Carbonate, and Acetal Rotaxanes by Anion Template Assistance and their Hydrolytic Dethreading

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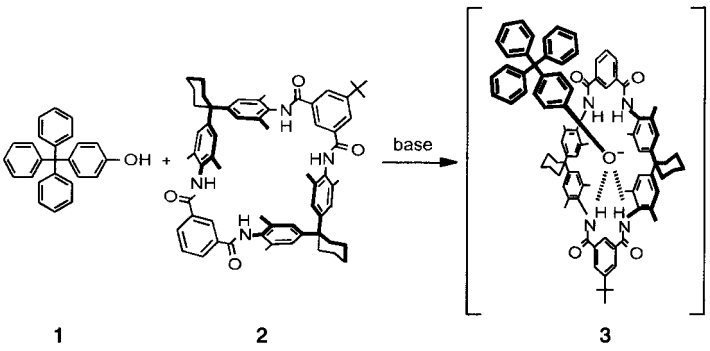
**Abstract:** New high-yield, threading syntheses of rotaxanes with ester, carbonate and acetal axles are reported. A phenolate anion is bound as a guest by a macrocycle, which acts as a concave template, to form a supramolecular wheeled nucleophile. This nucleophile can then react directly with appropriate components to form different types of rotaxanes. This method was used to synthesize two kinds of diester rotaxanes, which differ in that the ester groups are arranged in opposite directions, according to whether the phenolic functionality was located at the stopper component or at the axle precursor. Use of triphenylacetic acid chloride and *p*-tritylphenol as the complementary reactive axle building blocks led to a rotaxane with only one ester functionality in the axle. This single ester rotaxane contains the shortest rotaxane axle known so far. A rotaxane with a carbonate axle is formed from the reaction between trichloromethylchloroformate and (wheeled) phenolate blocking groups. A similar reaction between dichloromethane, used as both solvent and reagent, and the (wheeled) phenolate stoppers results in the corresponding acetal rotaxane in 81% yield. The ester, carbonate and acetal axles of the rotaxanes have been hydrolysed; this leads to the release of their wheels.

**Keywords:** macrocycles · molecular recognition · supramolecular chemistry · template effect · wheeled reagents

## Introduction

Rotaxanes and catenanes are molecules that consist of noncovalently interlocked building blocks. They are of current interest as model systems for molecular recognition and as precursors for molecular devices.[1] Their synthesis is usually based on template assistance, for example, the preorganization of building blocks by metal coordination, hydrophobic and donor–acceptor interactions, or hydrogen bonding.[2] The often rather low yields in the synthesis of uncharged rotaxanes[3] have been improved with the development of more efficient template strategies, such as the new synthesis of ether rotaxanes from anion templates in almost quantitative yields.[4] This synthesis has a reverse similarity to the rotaxane formation introduced by Stoddart et al.:[2b] the template is made by preorganization of a phenolate anion such as deprotonated **1** and a macrocyclic tetralactam **2**[5] into a supramolecular complex **3** (Scheme 1). According to NMR experiments, molecular recognition results from the interaction between the phenolate oxygen and at least one of the two isophthalamide units of the wheel **2**,[6] whose hydrogens are pointing towards the cycle's centre, as shown by several X-ray structure analyses.[7] The supramolecular nucleophile **3**, which was formed in this way, and can be considered to be a wheeled phenolate, can now generate a rotaxane by an $S_N$ reaction with a suitably functionalized electrophilic axle centre piece or stoppers.




1 2 3

Scheme 1. Formation of a supramolecular nucleophile **3** (wheeled phenolate) as a precursor for rotaxane synthesis.

## Results and Discussion

Here we report an extension of this new method to form rotaxanes with ester, carbonate and acetal axles by four different synthetic pathways. Firstly, we describe the reaction of an activated carboxylic acid building block with a phenolate (routes A and B, Scheme 2). For these routes the formation of the phenolate anion template complex is

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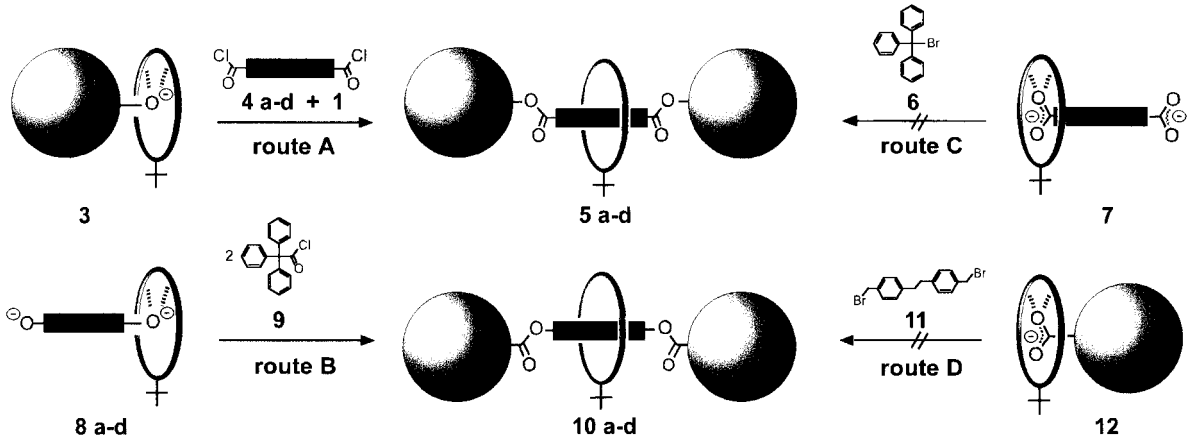



Scheme 2. Synthesis of rotaxanes with diester axles **5a–d** and **10a–d**.

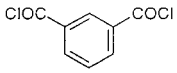
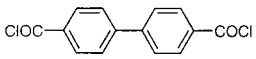
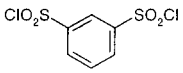
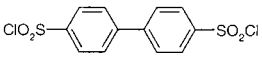
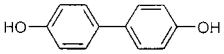
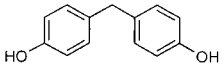
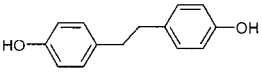
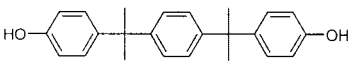
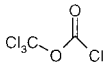
essential for the preferential formation of rotaxanes over the competing formation of the free axles. Secondly, we aimed to form ester axles by reaction between carboxylate anions and suitable alkylating agents (routes C and D, Scheme 2). In contrast to the first method, quantitative complexation of carboxylate anions by the tetralactam is the basic mechanistic step for rotaxane formation. For all these cases, the anionic functional group can be located either at the stopper component or at the axle centre piece.

However, only routes A and B, via phenolate anion templates, were successful. Selective deprotonation of the phenolic component, without affecting the carbonamide protons of the wheel, was achieved with equivalent amounts of potassium carbonate with a tenth equivalent of [18]crown-6 in dichloromethane and chloroform. The crown ether increases the solubility of potassium carbonate and also prevents the formation of a strong ion pair between the phenolate anion and the potassium cation, which would reduce both the nucleophilic reactivity and the complexation tendency of the phenolate anion.

Typical, and more polar, solvents for $S_N$ reactions, such as acetone, ether or dimethylformamide were not used, because they would reduce the affinity of the tetralactam for the phenolates. In addition, the components (especially the wheel) are sparingly soluble in these solvents.

Table 1 summarizes the building blocks employed and the resulting yields.[8] The reactivity and the length of the axle

Table 1. Overview of the building blocks used for the two synthetic routes A and B, as well as the carbonate, acetal and single ester routes.

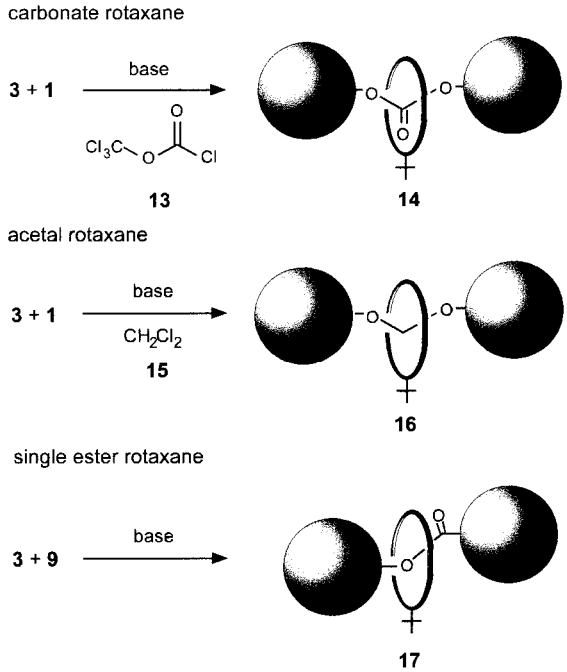
| Axle centre part | | Stopper component | Yield [%] |
|---|---|---|---|
|  | **4a** | **1** | 20 |
|  | **4b** | **1** | 19 |
|  | **4c** | **1** | 16 |
|  | **4d** | **1** | 14 |
|  | **20a** | **9** | 45 |
|  | **20b** | **9** | 46 |
|  | **20c** | **9** | 63 |
|  | **20d** | **9** | 65 |
|  | **13** | **1** | 26 |
| $CH_2Cl_2$ | **15** | **1** | 81 |
| | | **9+1** | 18 |

**Abstract in German:** *Mittels der hier beschriebenen Syntheseverfahren gelang erstmals ein effizienter Zugang zu neuartigen Rotaxanen mit Ester-, Carbonat- und Acetal-Achsen. Phenolat-Anionen bilden mit den Carbonamid-NH-Gruppen eines Tetralactam-Makrocyclus Wasserstoffbrückenbindungen und damit ein supramolekulares, beringtes Nucleophil. Ausgehend von diesen Supranucleophilen werden durch chemisches Einfädeln zwei Reihen unterschiedlicher Diester-Rotaxane hergestellt. Je nach Positionierung der Phenol-Gruppe – Anbindung entweder an den Stopperbaustein oder an den Achsenmittelstück-Vorläufer – entstehen Rotaxane mit jeweils entgegengesetzter Anordnung der Ester-Einheiten. Durch Verwendung von Triphenylessigsäurechlorid und p-Tritylphenol als komplementäre Achsenbausteine läßt sich ein Rotaxan mit nur einer Ester-Funktionalität in der Achse darstellen. Dieses Monoester-Rotaxan enthält wohl die bisher kürzeste bekannte Rotaxan-Achse überhaupt. Umsetzung von Trichloromethylchloroformiat mit zwei Äquivalenten p-Tritylphenolat in Anwesenheit des Tetralactam-Reifs führt zu einem Rotaxan mit Carbonat-Achse. Mit Dichlormethan als Lösungsmittel und zugleich Reagenz entsteht das entsprechende Acetal-Rotaxan in einer Ausbeute von 81 % in einstufiger Reaktion. Schließlich ist es möglich, durch saure Hydrolyse in Umkehrung des chemischen Einfädelns die Rotaxan-Achsen unter Freisetzung des Reifs zu spalten.*

precursors were varied to investigate the scope and applicability of our synthetic procedure.

Since phenols react with acid chlorides without prior deprotonation, which is a requirement for the formation of the supramolecular nucleophile, a large quantity (56–73%) of free axles was formed in the syntheses of **5a–d** (route A), **14**, and **17**. In the series of compounds with diphenolic axle centre pieces (route B), the yields increased substantially with increasing length of bisphenol (Table 1). A similar dependence of yield on the diacid dichloride lengths was not observed for route A.

An unexpected result was the formation of the acetal rotaxane **16**, at least in small amounts, in all the syntheses with *p*-tritylphenolate (**1**) in dichloromethane. This results from the reaction between the wheeled *p*-tritylphenolate stopper reagent **3** and the solvent. Therfore chloroform was used as the solvent, as it does not react in this way with *p*-tritylphenolate, and yields up to 26% were reached. Under the same reaction conditions with dichloromethane, but without addition of a diacid chloride electrophile, this side reaction was optimized to an 81% yield of the acetal rotaxane **16** (Scheme 3).




Scheme 3. Synthesis of carbonate, acetal and single ester rotaxanes **14, 16** and **17**.

A rotaxane with a carbonate axle (**14**) was synthesized in 26% yield from trichloromethylchloroformate (**13**) as the axle centre piece precursor (Scheme 3). The reaction of the wheeled phenolate complex **3** with the acid chloride stopper **9** yielded 18% of a single ester rotaxane **17** (Scheme 3). The lower yield of this reaction relative to that of route B is not surprising, even though only one bond was formed, because both reaction components are sterically hindered. With only seven bonds between the two trityl methine carbons, this single ester rotaxane probably contains the shortest axle centre part ever incorporated into a rotaxane (Figure 1).[9]

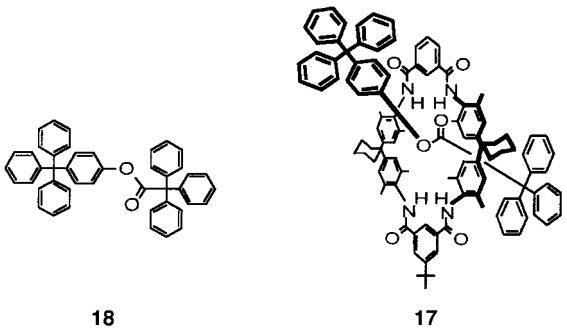
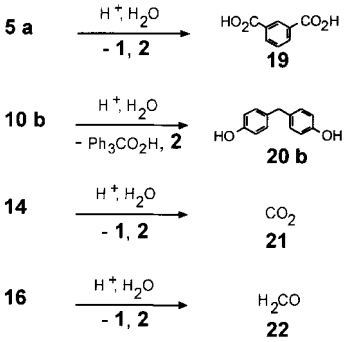



Figure 1. Axle **18** of the single ester rotaxane **17**.

The chemical reversal of the threading rotaxane synthesis (chemical dethreading) is easily achieved by hydrolysis of the ester and the acetal bonds of the rotaxanes, upon which the wheel and the axle building blocks are released (Scheme 4).




Scheme 4. Hydrolysis of selected rotaxanes: the ester, carbonate and acetal rotaxanes **5 a, 10 b, 14** and **16**.

## Conclusion

The results reported here for rotaxanes emphasize the wide scope and applicability of this new anion template assistance method for the synthesis of mechanically bound molecules. In contrast to already known and also very effective rotaxane syntheses, which are also based on ionic template assistance, this synthetic concept does not result in charged, but in electrically neutral rotaxanes. This is made possible by the use of an anionic precursor that acts as both templating agent and functional group for the threading reaction. We are currently investigating the threading syntheses, by $S_N$ and related reactions, of rotaxanes with different ionic guests as axle centre pieces or blocking groups.[10]

## Experimental Section

**General**: All solvents were distilled prior to use. 4-Tritylphenol (Lancaster), triphenylacetic acid (Lancaster), 3,5-di-*tert*-butylbenzoic acid (Lancaster), 4,4′-ethylenebisphenol (Aldrich), 4,4′-dihydroxybisphenol (Aldrich), 4,4′-dihydroxydiphenylmethane (Aldrich), 4,4′-(1,4-phenylenediisopropylidene)bisphenol (Aldrich), trichloromethylchloroformate (Merck), and all other chemicals were of the best commercial quality available and were used as received. The tetralactam macrocycle was prepared as reported previously.[5] Acid chlorides, if not commercially obtained, were synthesized and purified by standard procedures and not fully character-



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ized. Elemental analyses were done by the analytical facilities of the Kekulé-Institut für Organische Chemie und Biochemie of the University of Bonn. FAB-MS spectra were recorded on a Concept 1 H Kratos Analytical Manchester instrument with a matrix of *m*-nitrobenzoylalcohol. MALDI-TOF spectra were measured on MALDI-TofSpecE, Micromass, Manchester instruments, with matrixes of 9-nitroanthracene or 2,5-dihydroxybenzoic acid. $^1$H and $^{13}$C NMR spectra were recorded on AM 250 (62.9) MHz or AM 400 (100.6) MHz Bruker, Analytische Meßtechnik GmbH, Karlsruhe, spectrometers.

**General procedure for route A (rotaxanes 5a–d) and the syntheses of the carbonate rotaxane 14, the acetal rotaxane 16, and the single ester rotaxane 17**: A mixture of tetralactam cycle **2** (100 mg, 0.104 mmol), *p*-tritylphenol **1** (70 mg, 0.208 mmol), potassium carbonate (29 mg, 0.208 mmol) and dibenzo[18]crown-6 (8 mg, 0.021 mmol) in dry chloroform (5 mL) was cooled in an ice bath and stirred for 15 min. A solution of diacid dichloride **4a–d** (1 equiv, 0.104 mmol) in dry chloroform (3 mL) under argon was added over a period of 1.5 h. The reaction mixture was allowed to warm up slowly to room temperature and stirred for seven days. Then the solvent was removed under reduced pressure and the crude product was purified by column chromatography on silica gel with $CH_2Cl_2$/ethyl acetate (25:1). Yields are given in Table 1.

**Rotaxane 5a**: $R_f = 0.11$; yield 20% (36.7 mg, 0.021 mmol) as a colourless powder; m.p. 198 °C; $^1$H NMR (400 MHz, [D$_7$]DMF, 25 °C): $\delta = 1.38$ (s, 9H; *t*Bu $CH_3$), 1.50 (s, 4H; cyclohexanediyl $CH_2$), 1.59 (s, 8H; cyclohexanediyl $CH_2$), 1.92 (s, 24H; $CH_3$), 2.40 (s, 8H; cyclohexanediyl $CH_2$), 6.66 (d, $^3J$(H,H) = 8.8 Hz, 4H; phenolate), 7.11 (s, 8H; amidophenyl), 7.18–7.51 (m, 37H; trityl, isophthaloyl), 7.70 (t, $^3J$(H,H) = 7.3 Hz, 1H; isophthaloyl), 8.04 (d, 2H; $^3J$(H,H) = 7.3 Hz, isophthaloyl), 8.11 (s, 2H; 5-*t*Bu-isophthaloyl), 8.39 (s, 1H; isophthaloyl), 8.52 (s, 2H; amide), 8.59 (s, 2H; amide), 8.65 (s, 2H; 5-*t*Bu-isophthaloyl); $^{13}$C NMR (100.6 MHz, [D$_7$]DMF, 25 °C): $\delta$ = 18.9, 19.0 ($CH_3$), 23.5, 26.8, 35.8 (cyclohexanediyl $CH_2$), 31.4 (*t*Bu $CH_3$), 35.6 (*t*Bu Cq), 45.5 (cyclohexanediyl Cq), 65.3 (Cq), 120.9, 125.2, 126.8, 126.9, 127.0, 127.6, 128.3, 128.4, 128.5, 130.2, 130.3, 131.4, 131.6, 132.8, 135.5 (CH), 132.8, 133.3, 133.4, 135.5, 135.6, 135.7, 135.8, 145.1, 147.3, 147.4, 148.1, 148.9, 153.1 (Cq), 165.3, 165.5 (amide Cq), 165.7 (ester Cq); MALDI-TOF MS: *m*/*z* :calcd 1764.8 [$M^+$]; found 1764.8.

**Rotaxane 5b**: $R_f = 0.30$; yield 19% (36.4 mg, 0.020 mmol) as a colourless powder; m.p. 219 °C; $^1$H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta = 1.42$ (s, 9H; *t*Bu $CH_3$), 1.50 (s, 4H; cyclohexanediyl $CH_2$), 1.65 (s, 8H; cyclohexanediyl $CH_2$), 1.86 (s, 24H; $CH_3$), 2.27 (s, 8H; cyclohexanediyl $CH_2$), 6.71 (d, $^3J$(H,H) = 8.7 Hz, 4H; phenolate), 6.83 (s, 8H; aryl), 6.97 (d, $^3J$(H,H) = 8.7 Hz, 4H; phenolate), 7.00 (s, 2H; amide), 7.08–7.14 (m, 12H; trityl, amide), 7.15–7.22 (m, 21H; trityl, isophthaloyl), 7.71 (d, $^3J$(H,H) = 8.4 Hz, 4H; biphenyl), 7.72 (t, $^3J$(H,H) = 7.6 Hz, 1H; isophthaloyl), 7.81 (s, 1H; 5-*t*Bu-isophthaloyl), 8.01 (d, $^3J$(H,H) = 8.4 Hz, 4H; biphenyl), 8.25 (d, $^3J$(H,H) = 7.6 Hz, 2H; isophthaloyl), 8.27 (s, 2H; 5-*t*Bu-isophthaloyl); $^{13}$C NMR (62.9 MHz, $CDCl_3$, 25 °C): $\delta$ = 18.6, 18.7 ($CH_3$), 23.0, 26.8, 35.8 (cyclohexanediyl $CH_2$), 31.4 (*t*Bu $CH_3$), 35.5 (*t*Bu Cq), 45.3 (cyclohexanediyl Cq), 64.6 (Cq), 120.1, 121.2, 124.9, 126.4, 126.7, 127.8, 128.9, 129.3, 130.6, 130.8, 130.9, 131.0, 131.1, 132.1 (CH), 132.1, 134.5, 134.7, 134.8, 145.0, 146.5, 148.3, 148.7, 148.8 (Cq), 164.7, 165.2 (amide Cq), 166.1 (ester Cq); MALDI-TOF MS: *m*/*z*: calcd 1840.4 [$M$+Na$^+$], found 1863.8.

**Rotaxane 5c**: $R_f = 0.14$; yield 16% (30.6 mg, 0.01 mmol) as a colourless powder; m.p. 183 °C; $^1$H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta = 1.38$ (s, 9H; *t*Bu $CH_3$), 1.59 (s, 4H; cyclohexanediyl $CH_2$), 1.69 (s, 8H; cyclohexanediyl $CH_2$), 1.82 (s, 24H; $CH_3$), 2.32 (s, 8H; cyclohexanediyl $CH_2$), 6.20 (d, $^3J$(H,H) = 8.8 Hz, 4H; phenolate), 6.86–7.21 (m, 46H; amidophenyl, trityl, isophthaloyl), 7.39 (s, 2H; amide), 7.43 (s, 1H; isophthaloyl), 7.61 (s, 1H; isophthaloyl), 7.65 (t, $^3J$(H,H) = 7.6 Hz, 1H; isophthaloyl), 8.16 (d, $^3J$(H,H) = 7.6 Hz, 2H; isophthaloyl), 8.20 (s, 2H; 5-*t*Bu-isophthaloyl), 8.22 (s, 1H; 5-*t*Bu-isophthaloyl); $^{13}$C NMR (100.6 MHz, $CDCl_3$): $\delta$ = 18.8 ($CH_3$), 23.1, 26.4, 35.9 (cyclohexanediyl $CH_2$), 31.3 (*t*Bu $CH_3$), 35.6 (*t*Bu Cq), 45.4 (cyclohexanediyl Cq), 64.6 (Cq), 120.5, 120.9, 124.8, 126.6, 126.8, 126.9, 127.1, 127.1, 127.3, 127.7, 127.9, 129.3, 130.7, 130.9, 131.0, 131.1 (CH), 131.2, 132.1, 132.8, 133.1, 134.5, 134.7, 134.9, 135.0, 137.7, 145.0, 147.0, 149.1, 154.2 (Cq), 164.7, 165.2 (amide Cq); MALDI-TOF MS: *m*/*z*: calcd 1840.4 [$M$+Na$^+$], found 1863.8.

**Rotaxane 5d**: $R_f = 0.22$; yield 14% (27.8 mg, 0.015 mmol) as a colourless powder; m.p. 163 °C; $^1$H NMR (250 MHz, $CDCl_3$, 25 °C): $\delta = 1.40$ (s, 9H; *t*Bu $CH_3$), 1.53 (s, 4H; cyclohexanediyl $CH_2$), 1.69 (s, 8H; cyclohexanediyl $CH_2$), 1.88 (s, 24H; $CH_3$), 2.32 (s, 8H; cyclohexanediyl $CH_2$), 6.31 (d, $^3J$(H,H) = 8.5 Hz, 4H; phenolate), 6.87 (d, $^3J$(H,H) = 8.5 Hz, 4H; phenolate), 6.93 (s, 8H; amidophenyl), 6.98 (s, 2H; amide), 7.02–7.31 (m, 38H; trityl, biphenyl), 7.44 (s, 1H; isophthaloyl), 7.64 (s, 1H; amide), 7.70 (t, $^3J$(H,H) = 7.8 Hz, 1H; isophthaloyl), 7.92 (s, 1H; 5-*t*Bu-isophthaloyl), 7.97 (s, 1H; amide), 8.19 (d, $^3J$(H,H) = 7.6 Hz, 2H; isophthaloyl), 8.21 (s, 2H; 5-*t*Bu- isophthaloyl); $^{13}$C NMR (100.6 MHz, $CDCl_3$, 25 °C): $\delta$ = 18.8 ($CH_3$), 23.1, 26.4, 35.9 (cyclohexanediyl $CH_2$), 31.3 (*t*Bu $CH_3$), 35.5 (*t*Bu Cq), 45.4 (cyclohexanediyl Cq), 64.6 (Cq), 120.5, 120.9, 121.4, 123.5, 126.3, 126.4, 126.9, 127.5, 127.7, 127.8, 128.1, 128.2, 129.3, 131.1 (CH), 131.1, 132.1, 132.6, 134.5, 134.7, 135.0, 136.1, 144.6, 146.1, 146.2, 146.5, 146.6, 149.2, 154.3 (Cq), 164.8, 165.3 (amide Cq); MALDI-TOF MS: *m*/*z*: calcd 1912.5 [$M$+Na$^+$], found 1936.0.

**Carbonate rotaxane 14**: Compound **14** was prepared in the same way as described above, but with trichloromethylchloroformate **13** (18.2 mg, 0.104 mmol) instead of the diacid dichloride component. $R_f = 0.28$; yield 26% (44.9 mg, 0.027 mmol) as a colourless powder; m.p. 192 °C; $^1$H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta = 1.40$ (s, 9H; *t*Bu $CH_3$), 1.51 (s, 4H; cyclohexanediyl $CH_2$), 1.64 (s, 8H; cyclohexanediyl $CH_2$), 1.82 (s, 24H; $CH_3$), 2.23 (s, 8H; cyclohexanediyl $CH_2$), 5.88 (d, 4H; $^3J$(H,H) = 8.7 Hz, phenolate), 6.88 (s, 8H; aryl), 6.90 (s, 2H; amide), 6.92 (d, $^3J$(H,H) = 8.7 Hz, 4H; phenolate), 6.99 (m, 12H; trityl, amide), 7.15 (m, 20H; trityl), 7.55 (s, 1H; isophthaloyl), 7.68 (t, $^3J$(H,H) = 7.8 Hz, 1H; isophthaloyl), 7.78 (s, 1H; 5-*t*Bu-isophthaloyl), 8.22 (d, $^3J$(H,H) = 7.8 Hz, 2H; isophthaloyl), 8.28 (s, 2H; 5-*t*Bu-isophthaloyl); $^{13}$C NMR (62.9 MHz, $CDCl_3$, 25 °C): $\delta$ = 18.7 ($CH_3$), 23.4, 26.4, 35.9 (cyclohexanediyl $CH_2$), 31.3 (*t*Bu $CH_3$), 35.5 (*t*Bu Cq), 45.3 (cyclohexanediyl Cq), 64.5 (Cq), 119.2, 121.1, 123.7, 126.5, 126.8, 127.9, 129.3, 130.4, 130.8, 131.0, 132.1, 132.4 (CH), 134.3, 134.5, 134.8, 146.0, 146.4, 148.0, 149.1, 153.3, 154.3 (Cq), 164.5, 165.0 (amide Cq) 159.9 (carbonate Cq); MALDI-TOF MS: *m*/*z*: calcd 1660.2 [$M^+$], found 1660.9; Elemental analysis: calcd for $C_{115}H_{110}N_4O_7 \cdot C_8H_{16}O_4$: C 80.45, H 6.91, N 3.05; found: C 80.10, H 6.74, N 2.99.

**Acetal rotaxane 16**: The preparation of **16** required the use of tetralactam cycle **2**, two equivalents of *p*-tritylphenol **1**, potassium carbonate and dibenzo[18]crown-6 under the conditions described above. $R_f = 0.28$; yield 81% (138.6 mg, 0.084 mmol) as a colourless powder; m.p. 194–197 °C; $^1$H NMR (400 MHz, [D$_7$]DMF, 25 °C): $\delta = 1.38$ (s, 9H; *t*Bu $CH_3$), 1.51 (s, 4H; cyclohexanediyl $CH_2$), 1.60 (s, 8H; cyclohexanediyl $CH_2$), 1.89 (s, 24H; aryl $CH_3$), 2.39 (s, 8H; cyclohexanediyl $CH_2$), 4.08 (s, 2H; acetal $CH_2$), 6.19 (d, $^3J$(H,H) = 8.8 Hz, 4H; phenolate), 7.00 (d, $^3J$(H,H) = 8.8 Hz, 4H; phenolate), 7.03 (s, 8H; amidophenyl), 7.25 (m, 30H; trityl), 7.71 (t, $^3J$(H,H) = 7.6 Hz, 1H; isophthaloyl), 8.01 (s, 1H; isophthaloyl), 8.10 (d, $^3J$(H,H) = 7.6 Hz, 2H; isophthaloyl), 8.40 (s, 2H; 5-*t*Bu-isophthaloyl), 8.55 (s, 1H; 5-*t*Bu-isophthaloyl), 8.79 (s, 2H; amide), 8.81 (s, 2H; amide); $^{13}$C NMR (100.6 MHz, [D$_7$]DMF, 25 °C): $\delta$ = 19.1, 19.2 (aryl $CH_3$), 23.5, 26.8, 35.9 (cyclohexanediyl $CH_2$), 31.4 (*t*Bu $CH_3$), 45.5 45.6 (cyclohexanediyl Cq), 64.9 (Cq), 92.3 (acetal $CH_2$), 116.1, 126.1, 126.5, 126.6, 126.9, 128.2, 128.3, 128.5, 129.9, 131.3, 131.4, 132.4 (CH), 132.7, 133.6, 133.7, 135.5, 135.6, 135.7, 140.9, 141.2, 147.6, 153.1, 155.0, 155.6 (Cq), 165.6, 165.8 (amide Cq); MALDI-TOF MS: *m*/*z*: calcd 1646.2 [$M$+Na$^+$], found 1668.7; $C_{115}H_{112}N_4O_8 \cdot C_4H_8O_2$ (1766.28): calcd C 82.51, H 6.87, N 3.23; found: C 82.25, H 6.90, N 3.17.

**Single ester rotaxane 17**: The synthesis of **17** required equimolar amounts of triphenylacetic acid chloride **9** and *p*-tritylphenol **1**. Compound **9** was added directly to the mixture of the other reactants under the above-mentioned conditions. $R_f = 0.24$; yield 18% (29.3 mg, 0.019 mmol) as a colourless powder; m.p. 187 °C; $^1$H NMR (250 MHz, $CDCl_3$, 25 °C): $\delta$ = 1.41 (s, 9H; *t*Bu $CH_3$), 1.49–1.82 (m, 36H; aryl $CH_3$, cyclohexanediyl $CH_2$), 2.29 (s, 8H; cyclohexanediyl $CH_2$), 5.05 (d, $^3J$(H,H) = 8.6 Hz, 2H; phenolate), 6.30 (d, $^3J$(H,H) = 8.6 Hz, 2H; phenolate), 6.68–7.25 (m, 42H; trityl, amidophenyl, amide), 7.62 (s, 1H; isophthaloyl), 7.64 (t, $^3J$(H,H) = 7.7 Hz, 1H; isophthaloyl), 7.88 (s, 1H; 5-*t*Bu-isophthaloyl), 8.11 (d, $^3J$(H,H) = 7.7 Hz, 2H; isophthaloyl), 8.12 (s, 2H; 5-*t*Bu-isophthaloyl); $^{13}$C NMR (62.9 MHz, $CDCl_3$, 25 °C): $\delta$ = 18.5 (aryl $CH_3$), 23.2, 26.4, 36.3 (cyclohexanediyl $CH_2$), 31.4 (*t*Bu $CH_3$), 35.5 (*t*Bu Cq), 45.5 (cyclohexanediyl Cq), 64.5, 67.4 (Cq), 119.5, 120.2, 122.2, 124.9, 127.1, 127.6, 127.7, 127.9, 128.1, 129.2, 129.8, 130.3, 131.1, 132.1, 132.2 (CH), 126.1, 131.2, 134.7, 134.8, 135.1, 135.2, 141.4, 146.4, 148.6, 148.8, 154.2 (Cq), 165.3, 165.8 (amide Cq), 176.9 (ester Cq); MALDI-TOF MS: *m*/*z*: calcd 1568.1 [$M$+Na$^+$], found 1591.1.

**General procedure for route B (10a–d)**: A mixture of tetralactam cycle **2** (100 mg, 0.104 mmol), the bisphenolic component **20 a–d** (1 equiv, 0.104 mmol), triphenylacetic acid chloride **9** (63 mg, 0.208 mmol), potassium carbonate (29 mg, 0.208 mmol) and [18]crown-6 (5 mg, 0.021 mmol) in dry dichloromethane (10 mL) was cooled in an ice bath. The reaction mixture was allowed to warm up slowly to room temperature and stirred for seven days. The solvent was removed under reduced pressure, and the crude product was purified by column chromatography ($SiO_2$, 63–100 $\mu$m) with $CH_2Cl_2$/ethyl acetate (25:1). Yields are given in Table 1.

**Rotaxane 10a**: $R_f = 0.41$; yield 45% (74.2 mg, 0.047 mmol) as a colourless powder; m.p. >340 °C; $^1$H NMR (250 MHz, $CDCl_3/CD_3OD$, 25 °C): $\delta =$ 1.29 (s, 9H; *t*Bu $CH_3$), 1.40 (s, 4H; cyclohexanediyl $CH_2$), 1.51 (s, 8H; cyclohexanediyl $CH_2$), 1.63 (s, 24H; aryl $CH_3$), 2.20 (s, 8H; cyclohexanediyl $CH_2$), 5.98 (d, $^3J$(H,H) = 8.4 Hz, 4H; biphenyl), 6.39 (d, $^3J$(H,H) = 8.4 Hz, 4H; biphenyl), 6.87–7.18 (m, 42H; trityl, amidophenyl, amide), 7.31 (s, 1H; isophthaloyl), 7.45 (t, $^3J$(H,H) = 7.8 Hz, 1H; isophthaloyl), 7.50 (s, 1H; 5-*t*Bu-isophthaloyl), 7.82 (d, $^3J$(H,H) = 7.8 Hz, 2H; isophthaloyl), 7.89 (s, 2H; 5-*t*Bu-isophthaloyl); $^{13}$C NMR (100.6 MHz, $CDCl_3/CD_3OD$, 25 °C): $\delta =$ 18.2 (aryl $CH_3$), 22.7, 24.0, 35.7 (cyclohexanediyl $CH_2$), 30.7 (*t*Bu $CH_3$) 5.0 (*t*Bu Cq), 45.0 (cyclohexanediyl Cq), 67.3 (Cq), 121.2, 123.1, 125.8, 126.5, 126.8, 127.3, 127.7, 127.8, 128.6, 129.7, 129.9, 131.5 (CH), 130.7, 130.1, 133.7, 133.9, 134.9, 135.0, 136.4, 141.3, 148.7, 149.9, 15.7 (Cq), 166.1, 166.4 (amide Cq), 174.8 (ester Cq); FAB MS: *m*/*z*: calcd 1688.2 [$M^+$], found 1687.6; $C_{116}H_{110}N_4O_8 \cdot C_4H_8O_2 \cdot H_2O \cdot CH_4O$ (1286.33): calcd C 79.58, H 6.84, N 3.07; found: C 79.33, H 6.44, N 3.15.

**Rotaxane 10b**: $R_f = 0.22$; yield 46% (75.0 mg, 0.046 mmol) as a colourless powder; m.p. 197–200 °C; $^1$H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta =$ 1.39 (s, 9H; *t*Bu $CH_3$), 1.56 (s, 4H; cyclohexanediyl $CH_2$), 1.70 (s, 8H; cyclohexanediyl $CH_2$), 1.83 (s, 24H; aryl $CH_3$), 2.39 (s, 8H; cyclohexanediyl $CH_2$), 3.73 (s, 2H; diaryl $CH_2$), 5.99 (d, $^3J$(H,H) = 8.2 Hz, 4H; aryl), 6.40 (d, $^3J$(H,H) = 8.2 Hz, 4H; aryl), 6.60 (s, 1H; amide), 6.62 (s, 1H; amide), 6.78–7.39 (m, 42H; trityl, amidophenyl, amide), 7.45 (s, 1H; isophthaloyl), 7.59 (t, $^3J$(H,H) = 7.6 Hz, 1H; isophthaloyl), 7.65 (s, 1H; 5-*t*Bu-isophthaloyl), 8.10 (d, $^3J$(H,H) = 7.6 Hz, 2H; isophthaloyl), 8.18 (s, 2H; 5-*t*Bu-isophthaloyl); $^{13}$C NMR (100.6 MHz, $CDCl_3$, 25 °C): $\delta =$ 18.6, 18.7 (aryl $CH_3$), 22.6, 23.0, 36.1 (cyclohexanediyl $CH_2$), 26.3 (ethylene $CH_2$), 31.2 (*t*Bu $CH_3$), 35.3 (*t*Bu Cq), 45.3 (cyclohexanediyl Cq), 67.3 (Cq), 115.2, 120.9, 121.5, 124.3, 126.4, 127.1, 127.3, 127.9, 129.1, 129.4, 129.9, 130.2 (CH), 130.8, 130.9, 131.9, 134.1, 134.3, 134.9, 137.8, 148.9, 149.1, 149.2, 154.1 (Cq), 164.8, 165.2 (amide Cq), 171.3 (ester Cq); FAB-MS: *m*/*z*: calcd 1702.2 [$M^+$], found 1702.8; $C_{117}H_{112}N_4O_8 \cdot C_{12}H_{24}O_6 \cdot H_2O$ (1994.34): calcd C 76.83, H 6.89, N 2.78; found: C 76.69, H 6.51, N 2.81.

**Rotaxane 10c**: $R_f = 0.44$; yield 63% (112.4 mg, 0.066 mmol) as a colourless powder; m.p. 215–217 °C; $^1$H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta =$ 1.40 (s, 9H; *t*Bu $CH_3$), 1.48 (s, 2H; ethylene $CH_2$), 1.49 (s, 2H; ethylene $CH_2$), 1.56 (s, 4H; cyclohexanediyl $CH_2$), 1.72 (s, 8H; cyclohexanediyl $CH_2$), 1.78 (s, 24H; $CH_3$), 2.39 (s, 8H; cyclohexanediyl $CH_2$), 5.67 (d, $^3J$(H,H) = 7.3 Hz, 4H; *p*-xylylene H), 6.47 (d, $^3J$(H,H) = 7.3 Hz, 4H; *p*-xylylene), 6.77 (s, 1H; amide), 6.79 (s, 1H; amide), 6.85 (s, 1H; amide), 6.91–7.29 (m, 39H; trityl, amidophenyl, amide), 7.44 (s, 1H; isophthaloyl), 7.56 (t, $^3J$(H,H) = 7.6 Hz, 1H; isophthaloyl), 7.59 (s, 1H; 5-*t*Bu-isophthaloyl), 8.10 (d, $^3J$(H,H) = 7.6 Hz, 2H; isophthaloyl), 8.19 (s, 2H; 5-*t*Bu-isophthaloyl); $^{13}$C NMR (100.6 MHz, $CDCl_3$, 25 °C): $\delta =$ 18.7, 18.8 ($CH_3$), 24.2, 26.3, 36.0 (cyclohexanediyl $CH_2$), 36.6 (*t*Bu $CH_3$), 40.6 (diaryl $CH_2$), 45.4 (cyclohexanediyl Cq), 60.4 (*t*Bu Cq), 67.4 (Cq), 120.9, 121.5, 124.2, 126.8, 127.3, 127.9, 128.1, 129.1, 129.9, 130.2, 131.9, 132.0 (CH), 131.0, 131.3, 132.1, 134.1, 134.2, 135.0, 135.1, 141.7, 143.2, 148.9, 149.0, 154.0 (Cq), 164.6, 165.1 (amide Cq), 174.5 (ester Cq); MALDI-TOF MS: *m*/*z*: calcd 1716.2 [$M$+$Na^+$], found 1739.4; $C_{118}H_{114}N_4O_8 \cdot C_4H_8O_2$ (1804.32): calcd C 81.21, H 6.81, N 3.11; found: C 80.91, H 6.70, N 3.10.

**Rotaxane 10d**: $R_f = 0.38$; yield 65% (125.0 mg, 0.068 mmol) as a colourless powder; m.p. 216 °C; $^1$H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta =$ 1.39 (s, 9H; *t*Bu $CH_3$), 1.42 (s, 12H; dimethylmethylene $CH_3$), 1.59 (s, 4H; cyclohexanediyl $CH_2$), 1.70 (s, 8H; cyclohexanediyl $CH_2$), 1.78 (s, 24H; $CH_3$), 2.38 (s, 8H; cyclohexanediyl $CH_2$), 6.79–7.41 (m, 54H; trityl, amidophenyl, amide), 7.44 (s, 1H; isophthaloyl), 7.59 (t, $^3J$(H,H) = 7.7 Hz, 1H; isophthaloyl), 7.68 (s, 1H; 5-*t*Bu-isophthaloyl), 8.12 (d, $^3J$(H,H) = 7.6 Hz, 2H; isophthaloyl), 8.21 (s, 2H; 5-*t*Bu-isophthaloyl); $^{13}$C NMR (100.6 MHz, $CDCl_3$, 25 °C): $\delta =$ 18.7, 19.0 ($CH_3$), 23.0, 26.3, 36.2 (cyclohexanediyl $CH_2$), 30.9 (dimethylmethylene $CH_3$), 31.2 (*t*Bu $CH_3$), 35.4 (*t*Bu Cq), 42.1 (dimethylmethylene Cq), 45.3 (cyclohexanediyl Cq), 67.4 (Cq), 121.3, 124.4, 126.9, 127.1, 127.3, 127.5, 127.8, 127.9, 128.0, 129.2, 130.1, 130.3, 130.9, 132.0 (CH), 127.8, 129.2, 130.2, 130.3, 131.0, 134.1, 134.3, 135.0, 135.1, 148.9, 149.0, 154.1 (Cq), 164.6, 165.1 (amide Cq), 174.1 (ester Cq); FAB-MS: *m*/*z*: calcd 1848.5 [$M$+$H^+$], found 1849.1; $C_{128}H_{126}N_4O_8 \cdot C_4H_8O_2 \cdot CH_2Cl_2$ (2021.27): calcd C 79.02, H 6.78, N 3.51; found: C 79.05, H 6.69, N 3.61.

**Hydrolysis of the ester rotaxanes 5a and 10b, the carbonate rotaxane 14, and the acetal rotaxane 16**: A solution of the rotaxane (0.05 mmol), THF (10 mL) and hydrochloric acid (1 mL, 37%) was stirred for 1 day at room temperature. The course of the ester saponification was followed by thin layer chromatography.


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[6] The measured complexation induces a downfield shift in the position of the $^1$H NMR peak of the NH protons of the tetralactam host **2.** The values are shifted by 1.7 to 1.8 ppm (cf. [4]).

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[10] Since the submission of this paper the new method has been successfully applied to the syntheses of rotaxanes with thioether and thioester axles.

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