Rotaxane Assemblies with Dendritic Architecture

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Dedicated to Prof. Dr. S. Hünig on the occasion of his 80th birthday

Abstract: Strategies towards the synthesis of well-defined, mechanically interlocked, dendritic assemblies of rotaxanes are developed, one using a divergent, and the other a convergent approach. For the first time covalent bonds are not directly involved in the branching of dendrimers, only mechanical bonds act as unique branching elements.

Keywords: dendrimers; mechanical bonds; networks; rotaxanes; supramolecular chemistry

Introduction

Although rotaxanes are a rather new research area, some work has been done to connect these as building blocks in order to achieve assemblies. Non-polymeric structures are known in which functionalized rotaxane units are connected by covalent bonds between their macrocycles[1] (II in Figure 1) or axles[2] (I). In addition, a linear oligorotaxane, which consists of semirotaxane sub-units connected via hydrogen bonds was synthesized by Stoddart et al.[3] (III). Two-dimensional[4] (IV) and three-dimensional[5] (V) polyrotaxanes were reported by Kim et al. using metal-complexes as branching units. Networks were also achieved by Gibson et al.[6] (VI). They connected polymer chains containing rotaxanes as substituents with each other by threading one macrocycle into another. This double-strand polyrotaxane exhibited extremely different physical properties compared with the non-connected polymeric chain.

All these examples show a successful connection of oligo- or polymeric structures composed of rotaxane units. Except for systems I and II, these compounds are not of a defined composition. It is therefore a special challenge to design molecules where supramolecular binding sites offer a connection and at the same time control the stoichiometry of the assembly. It is anticipated that these unprecedented architectures will give rise to new physical properties in comparison with those of conventional flexible polymer chains.[7]

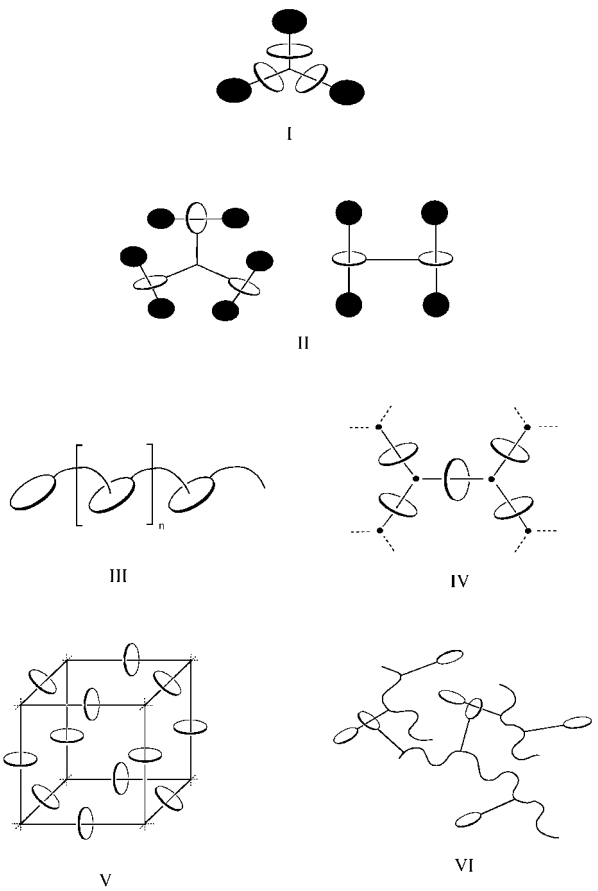

Figure 1. Known rotaxane assemblies; I: axle-linked assembly; II: wheel-linked assembly; III: linear one-dimensional oligorotaxane; IV: two-dimensional polyrotaxane; V: three-dimenional polyrotaxane; VI: rotaxane network.

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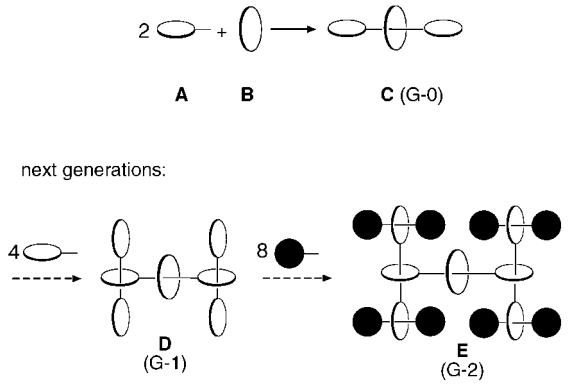
Here we report a new concept to connect rotaxanes to defined structures using mechanical bonds. The architecture of such molecules follows the building principle of dendrimers. These are composed of a core unit with branches pointing in different directions and with end groups forming the periphery.[8] To use rotaxanes for a structure like this, suitable mechanical branching units must replace the usual covalent branching connections. Thus, it is possible to design rotaxanes in such a way that they contain, instead of the usual stopper, macrocyclic units that can act as wheels. These are then, depending on their size, sterically large enough to fulfil their function as a stopper and in addition make a threading and trapping of a guest axle possible. This new function in a rotaxane allows us to build up specific rotaxane assemblies of different "generations".

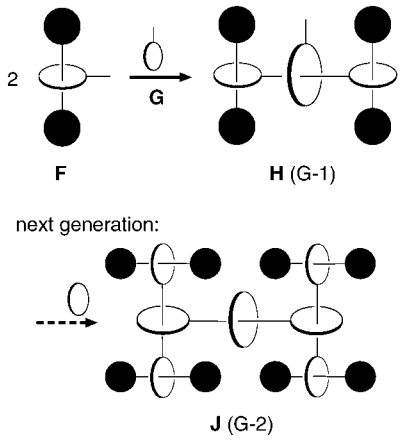
Generally, there are two approaches to synthesizing such molecules which are analogues to dendrimers. Both synthetic strategies, the divergent and the convergent, have been used by us to construct the first representatives of their class. In the divergent method the rotaxane assembly is built up from the core to the periphery. Scheme 1 shows the general construction principle.



Scheme 1. General concept for the divergent synthesis of rotaxane assemblies of increasing generation (G).

First, two wheels **A** – each containing a reactive functional group – are reacted with a suitable axle in the presence of a macrocycle **B**, thus forming a rotaxane **C** of generation zero.[9] To obtain a stable rotaxane **C**, the outer two macrocycles have to be large enough in size so that dethreading cannot take place. In the second reaction, the available coordination sites of the two outer wheels are used to trap two more stoppered axles. This leads to the assembly **D** which is of generation one. Continuing this strategy the formation of higher generations should be possible. If non-cyclic, but classical, sterically demanding stoppers are used in the last reaction step, a dendritic multirotaxane[10] molecule **E** of the second generation is formed and then further growth towards (mechanically connected) higher generations is no longer possible.

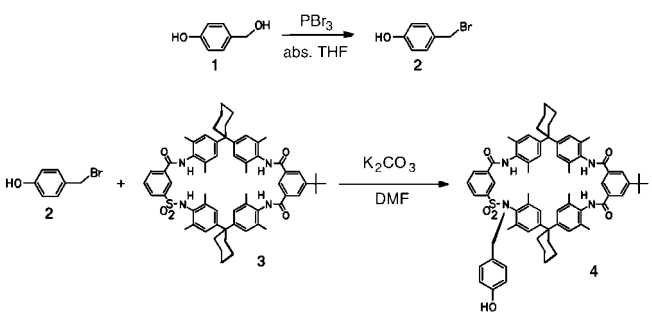
There is a second, basic method of constructing the assembly: the convergent strategy. Here, the molecule is built up from the periphery to the core. The synthesis starts with a protected wheel from which a rotaxane **F** is formed. After removing the protective group, rotaxane **F** reacts in the presence of a wheel **G** to form the rotaxane assembly **H** of the first generation. If the central wheel carries a functional group, it can be reacted further to form the assembly **J** of the second generation.



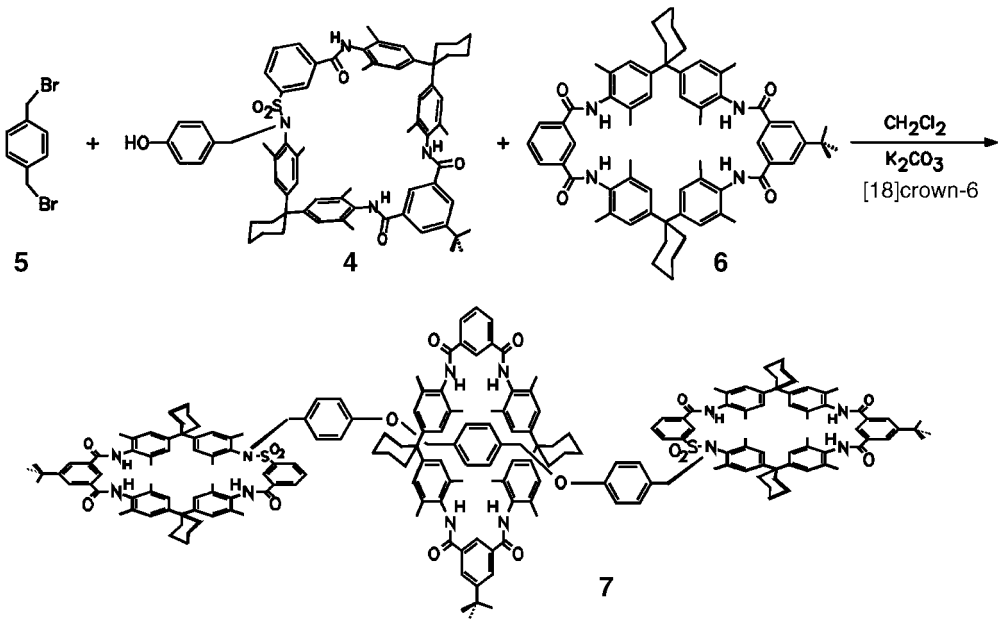
Scheme 2. Convergent synthesis of rotaxane assemblies.

Results and Discussion

The well-established "anion template method"[11] was used for the synthesis of rotaxanes in the divergent strategy. First, the wheels that were to act as stoppers had to be synthesized (Scheme 3). 4-Hydroxybenzyl alcohol **1** was reacted with phosphorous tribromide and pyridine as base in absolute tetrahydrofuran at –5 °C to yield the bromide **2**.[12] Then, a functionalization at the single sulfonamide group in the amide wheel **3**[13] was carried out with the bromomethyl compound **2** to give a wheel with a phenol-functionalized side chain. As **2** is not a stable compound the wheel **3** was added *in situ*.



Scheme 3. Synthesis of the wheel acting as stopper.



Scheme 4. Divergent synthesis of a rotaxane assembly in the generation zero.

The phenolic "stopper wheel" **4** was then used for the synthesis of the rotaxane **7**, by reacting it with 1,4-bis(bromomethyl)benzene **5** as the axle part in the presence of a tetralactam wheel **6**[14] (Scheme 4). The reaction was carried out in dichloromethane with potassium carbonate as a base at room temperature, yielding 56% of **7**. This molecule is a representative of generation zero and was characterized by MALDI-Tof and NMR spectroscopy.

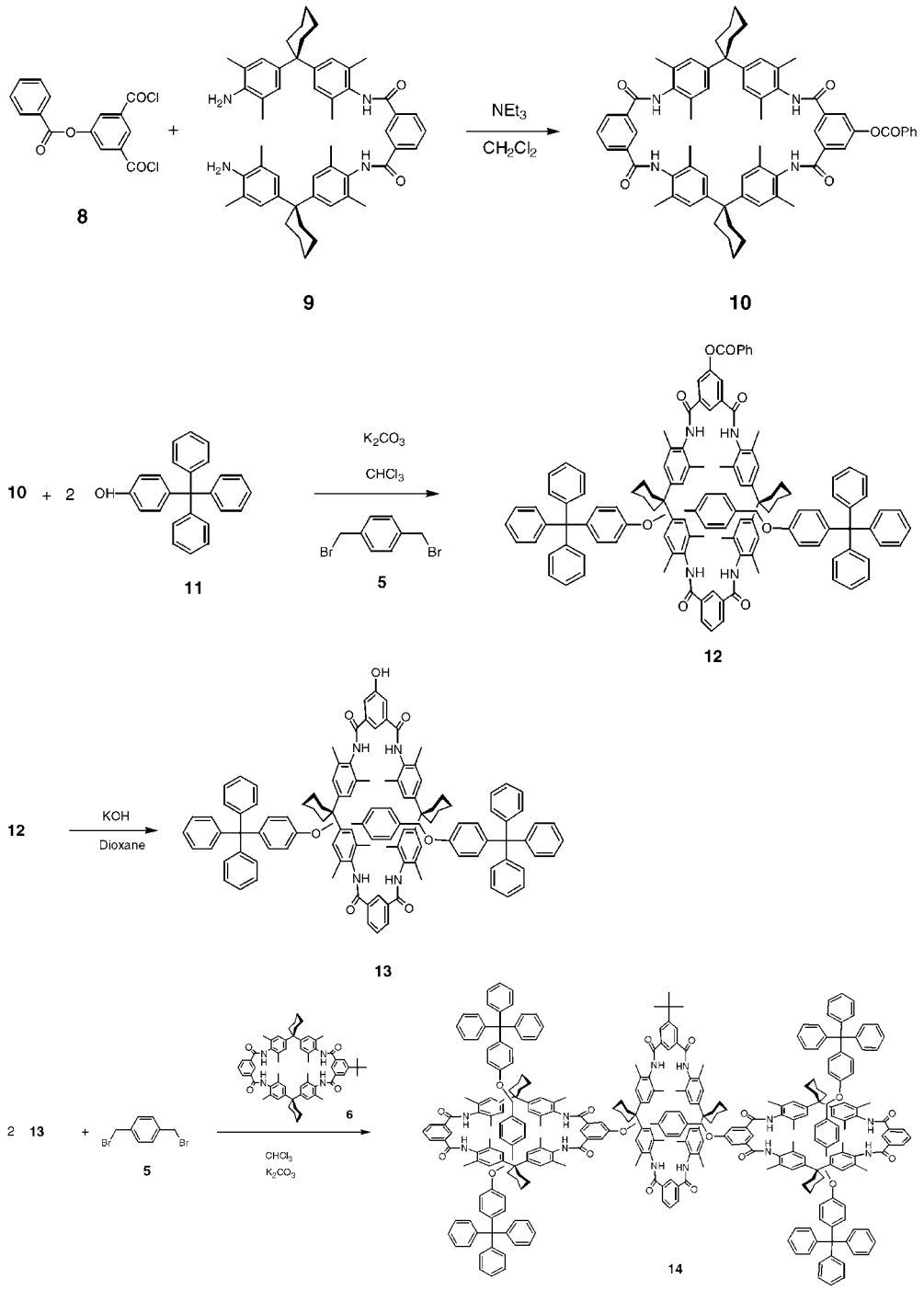
In contrast to the synthesis described above, an alternative one using the inverse polarity of the reactants was performed, i. e., with a phenolic axle part and a benzyl bromide-functionalised wheel, but it gave only poor yields. This suggests that this "inverted system" is less suitable for this type of rotaxane synthesis.

Reactions with the rotaxane **7** to form higher generations failed. It was only possible to thread one of the two terminal macrocycles, yielding an assembly of generation 0.5 in very small amounts. The cause of this lack of reactivity might be that the axle is relatively flexible and with one threaded wheel the template might be sterically hindered for further threading.

Based on the experiences mentioned above, we decided to design a synthesis using the convergent strategy. To form the building unit **F** (Scheme 2), we used the protected wheel **10** which was synthesized from 5-(benzoyloxy)isophthaloyl dichloride **8**[15] by reaction with diamine **9**[14] (Scheme 5). In the next step, the "stopper rotaxane" (mechanically bonded dendron **12**) was synthesized. Wheel **10** reacted with *p*-tritylphenol **11** and 1,4-bis(bromomethyl)benzene **5** in the presence of potassium carbonate in chloroform to form the rotaxane **12** using the "anion template effect" mentioned above. A deprotection step resulted in a rotaxane **13** which has a phenolic hydroxy group. This allowed a further connection to form the rotaxane assembly. The phenolic "stopper-rotaxane" **13** was reacted with 1,4-bis(bromomethyl)benzene **5** in the presence of the tetralactam wheel **6**[14] in chloroform with potassium carbonate as a base. Rotaxane **14** was formed in a yield of 39% and could be characterized completely by MALDI-Tof and NMR spectroscopy (for details see Experimental Section).

Conclusion and Outlook

Comparing the two different synthetic strategies that were applied, it can be stated that the general advantages of convergent strategies in synthesizing dendrimers also appeared in this case. Dendrimers that are built by divergent synthesis often have certain structural defects because many functional groups have to react quantitatively in one synthetic step. In our example of divergent strategy two even more difficult threading reactions were needed to form the first generation assembly (**D** in Scheme 1). In fact only one single threading succeeded in forming small amounts. In comparison, there is always one reacting centre per reaction step in the convergent synthesis (**F** and **H** in Scheme 2). Furthermore, it seems that in the divergent method the threading process might be sterically hindered because the axle is quite flexible. In contrast, in the convergent synthesis the reaction centre might not be severely hindered and the reaction could possibly take place on the peripheral site



Scheme 5. Convergent synthesis of a dendritic rotaxane assembly **14** of generation one.

of the side chain connected to the wheel to build up the next generation. If the axle is not too short, steric hindrance in the course of connecting the two "stopper-rotaxanes" (**F** and **H** in Scheme 2) should not have a big effect. In summary, the convergent strategy in the synthesis of the rotaxane assemblies of type **H** (Scheme 2) is favored.

In conclusion, new methods for connecting rotaxane units to assemblies are introduced using divergent and convergent synthesis strategies. For the first time in dendrimers the units are connected by mechanical bonds which are of uniform structure.

Based on our work we anticipate that higher generations of dendritic rotaxanes ("dendro-rotaxanes or rotaxa-dendrimers") can be generated using both new synthetic methods. Steric effects should be taken into account when bigger rotaxane components are linked. This might be circumvented with more rigid

axles of greater length. With regard to possible applications, the assemblies could play a role in the future construction of synthetic molecular machines or molecular networks[16] for technological applications.

Experimental Section

General Remarks

Solvents were purified by standard methods and dried if necessary. The reagents used were of commercial quality. TLC was carried out on silica gel 60 F 254 and column chromatography on silica gel 60, mesh size 63–100 μm (Merck, Darmstadt, Germany). Melting points were determined on a microscope heating unit form Reichert, Vienna and are not corrected. The NMR spectra were measured on AM-250 (^{1}H: 250 MHz, ^{13}C: 62.9 MHz) or on AM-400 (^{1}H: 400 MHz, ^{13}C: 100.6 MHz) spectrometers from Bruker Physik AG, Karlsruhe, Germany. All chemical shifts are quoted in ppm and the coupling constants are expressed in Hertz (Abbreviations: Iso: **iso**phthaloyl, 3Sb: **3-s**ulfonyl**b**enzoyl, tBi: 5-*tert*-**b**uty**l**i**s**ophthaloyl, TBME: *t*-butyl methyl ether, Cyh: cyclohexyl). FAB-MS: Concept 1H, Kratos Analytical Ltd. (matrix: *m*-nitrobenzyl alcohol). MALDI-MS: MALDI-Tof-Spec-E, Micromass, UK (matrix: 9-nitroanthracene, 2,5-dihydroxybenzoic acid).

4-Bromomethylphenol 2

Ref. [12]: 0.25 g (2 mmol) *p*-hydroxybenzyl alcohol were dissolved in 80 mL absolute tetrahydrofuran and were added at a temperature of –5 °C within 2.5 hours to a solution of 0.18 g (0.67 mmol) phosphorous tribromide and 2 drops of pyridine in 20 mL absolute tetrahydrofuran under an argon atmosphere. After the complete addition the solution was stirred for 12 more hours at room temperature. The mixture was filtered over celite and the residue was washed first with tetrahydrofuran and then with dichloromethane. The product was not isolated and was used for the next reaction immediately without removing the solvent.

Phenolic "Stopper Wheel" 4

A mixture of 0.90 g (0.90 mmol) of the sulfonamide wheel **3** and 0.63 g (4.50 mmol) of potassium carbonate were stirred in 60 mL dimethylformamide under an argon atmosphere for one day at a temperature of 40 °C. The solution containing **2** was added. The mixture was stirred for 2 more days at room temperature. Then the mixture was filtered and the solvent was removed by distillation. The remaining residue was purified by column chromatography; mp > 300 °C; R_f = 0.22 (CH_2Cl_2/TBME, 20/1); yield: 0.60 g (60%); ^{1}H NMR (400 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 1.25 (s, 9 H, CH_3), 1.34 (br, 8 H, CH_2), 1.62 (br, 4 H, CH_2), 1.92 (s, 6 H, CH_3), 2.07 (s, 6 H, CH_3), 2.21 (s, 6 H, CH_3), 2.23 (s, 6 H, CH_3), 2.00–2.41 (br, 8 H, CH_2), 4.26 (s, 2 H, benzyl-H), 6.56 (d, 2 H, ^3J = 8.4 Hz, arom. H), 6.71 (d, 2 H, ^3J = 8.4 Hz, arom. H), 6.91 (s, 4 H, arom. H), 7.01 (s, 4 H, arom. H), 7.68 (t, ^3J = 7.9 Hz, 1 H, 3Sb-H), 7.92 (s, 2 H, tBi–H), 8.12 (d, ^3J = 7.9 Hz, 1 H, 3Sb–H), 8.17 (s, 1 H, 3Sb–H), 8.19 (s, 1 H, 3Sb–H), 8.30 (s, 1 H, tBi–H); ^{13}C NMR (100.6 MHz, $CDCl_3$, 25 °C): δ = 19.7, 19.8, 20.0, 20.4, 32.7 (CH_3), 24.2, 24.4, 27.6, 27.8, 32.4, 32.8, 36.5, 36.6, 38.1, 46.4 (CH_2), 35.0, 46.5, 55.1 (Cq), 116.2, 124.7, 126.9, 127.1, 127.8, 128.5, 128.9, 130.3, 130.4, 130.7, 131.5, 131.7 (CH), 132.4, 132.8, 132.9, 134.7, 135.1, 135.4, 136.4, 136.6, 136.7, 144.3, 144.7, 144.8, 154.5, 158.1 (Cq), 164.7, 166.9, 168.3 (C=O); FAB-MS: *m/z* = 1103.5 [M^+ – H].

Rotaxane 7

96 mg (0.1 mmol) of the tetralactam wheel **6**[14], 230 mg (0.2 mmol) of the stopper wheel **4**, 26 mg (0.1 mmol) 1,4-bis(bromomethyl)benzene **5**, 14 mg (0.1 mmol) potassium carbonate, and 1 mg [18]crown-6 were stirred in 25 mL absolute dichloromethane for 6 days at room temperature. Then the mixture was diluted with 100 mL trichloromethane, filtered, and the solvents were removed by distillation. Purification was achieved by column chromatography; mp > 300 °C; R_f = 0.09 (CH_2Cl_2/CH_3OH, 35/1); yield: 180 mg (56%); ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 1.29 (br, 8 H, CH_2), 1.40 (s, 9 H, CH_3), 1.42 (s, 18 H, CH_3), 1.55 (br, 16 H, CH_2), 1.65 (br, 20 H, CH_2), 1.78 (s, 10 H, CH_3), 1.89 (s, 26 H, CH_3), 2.02 (s, 4 H, CH_2), 2.08 (s, 12 H, CH_3), 2.22 (s, 26 H, CH_3), 2.35 (br, 12 H, CH_2), 2.50 (br, 4 H, CH_2), 4.20 (s, 4 H, CH_2), 6.16 (s, 4 H, arom. H), 6.41 (d, ^3J = 8.4 Hz, 4 H, arom. H), 6.78 (br, 2 H, arom. H), 6.87 (d, ^3J = 8.4 Hz, 4 H, arom. H), 6.93 (s, 6 H, arom. H), 7.03 (s, 8 H, arom. H), 7.10 (s, 8 H, arom. H), 7.61 (s, 1 H, Iso-H), 7.64 (t, ^3J = 7.6 Hz, 1 H, Iso-H), 7.70 (t, ^3J = 7.6 Hz, 2 H, 3Sb–H), 7.81 (s, 1 H, tBi–H), 8.06 (d, ^3J = 7.6 Hz, 2 H, Iso-H), 8.13 (s, 2 H, 3Sb–H), 8.16 (s, 1 H, tBi–H), 8.19 (s, 1 H, tBi–H), 8.22 (br, 4 H, tBi–H, 4 H, 3Sb–H), 8.30 (s, 2 H, tBi–H); ^{13}C NMR (62.9 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 14.2, 14.3 (CH_3), 18.6, 18.7, 18.8, 19.1, 21.0, 23.2, 23.3, 23.5, 26.7, 26.8, 26.9, 31.2, 31.4 (CH_2), 35.6, 35.7, 36.0, 45.5, 45.6, 45.8, 61.1, 134.2, 134.5, 134.6, 135.0, 135.5, 135.6, 135.7, 147.7, 154.0, 159.4 (Cq), 124.0, 126.2, 126.9, 127.1, 127.3, 127.6, 128.1, 129.3, 129.9, 131.9, 131.5, 131.9, 132.0, 132.1 (CH), 167.0, 167.1, 167.3, 167.5 (C=O); MALDI-MS: *m/z* = 3295.2 [M^+ + Na], 3311.2 [M^+ + K].

5-(Benzoyloxy)isophthalic Acid

Ref. [15]: 13.85 g (75 mmol) of 5-hydroxyisophthalic acid were dissolved in 100 mL water and 9.20 g (230 mmol) sodium hydroxide were added. This suspension was cooled with ice and within four hours a solution of 8.55 mL (75 mmol) benzoyl chloride in 50 mL diethyl ether was added. It was stirred for four more hours at room temperature. Then the organic phase was separated and the crude product was precipitated out of the aqueous phase after adding dilute hydrochloric acid. After filtration and washing with water the product was purified by crystallisation from acetone/water (1/1); mp 293 °C; yield: 20 g (92%); ^{1}H NMR [250 MHz, $(CD_3)_2CO$, 25 °C]: δ = 7.59 (t, ^3J = 7.5 Hz, 2 H, benzoyloxy-H), 7.70 (d, ^3J = 7.5 Hz, 2H, benzoyloxy-H), 8.16 (t, ^3J = 7.3 Hz, 1 H, benzoyloxy-H), 8.22 (s, 2 H, Iso-H), 8.59 (s, 1 H, Iso-H); ^{13}C NMR [62.9 MHz, $(CD_3)_2CO$, 25 °C]: δ = 128.2, 129.7, 131.0, 134.9 (CH), 128.8, 133.5 (Cq), 152.0 (C-O), 166.1 (C=O); FAB-MS: *m/z* = 287.1 [M^+], 307.0 [M^+ + Na – H], 329.0 [M^+ + 2Na – 2H].

5-(Benzoyloxy)isophthaloyl Dichloride 8

4.0 g (14 mmol) of 5-benzoyloxyisophthalic acid were heated under reflux for two hours in 50 mL (0.69 mol) thionyl chloride with addition of 2 drops of dimethylformamide. An excess of thionyl chloride was removed by distillation and the product was crystallized from petroleum ether (60–80 °C); mp 95 °C; yield: 0.9 g (19%); ^{1}H NMR (250 MHz, $CDCl_3$, 25 °C): δ = 7.55 (t, ^3J = 7.4 Hz, 2H, benzoyloxy-H), 7.70 (d, ^3J = 7.4 Hz, 2 H, benzoyloxy-H), 8.19 (t, ^3J = 7.2 Hz, 1 H, benzoyloxy-H), 8.28 (s, 2H, Iso-H), 8.74 (s, 1 H, Iso-H); ^{13}C NMR (62.9 MHz, $CDCl_3$, 25 °C): δ = 128.9, 130.4, 130.5, 130.6, 134.5 (CH), 128.0, 135.5 (Cq), 151.6 (C–O), 164.3 (COCl), 166.5 (C=O); FAB-MS: *m/z* = 321.6 [M$^+$], 286.9 [M$^+$ – Cl].

Protected Tetralactam Macrocycle 10

0.84 g (2.58 mmol) 5-benzoyloxyisophthaloyl dichloride **8** were dissolved in 250 mL trichloromethane and 2.00 g (2.58 mmol) *N*,*N*′-bis{4-[1-(4-amino-3,5-dimethylphenyl)cyclohexyl]-2,6-dimethylphenyl}isophthaloyl diamide **9** with addition of 0.67 mL triethylamine were dissolved in 250 mL trichloromethane. Both solutions were added simultaneously to 1.5 L of dichloromethane at room temperature within eight hours. Afterwards the solvents were removed by distillation and the product was purified using column chromatography; mp 302 °C; R_f = 0.44 (CH_2Cl_2/$CH_3CO_2C_2H_5$, 4/1); yield: 592 mg (22%); ^{1}H NMR (250 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 1.30 (br, 4 H, Cyh-CH_2), 1.41 (br, 8 H, Cyh–CH_2), 1.95 (s, 24 H, CH_3), 2.10 (br, 8 H, Cyh–CH_2), 6.77 (s, 8 H, arom. H), 7.32 (t, ^3J = 7.4 Hz, 2 H, benzoyloxy-H), 7.42 (t, ^3J = 7.7 Hz, 1 H, Iso-H), 7.45 (t, ^3J = 7.4 Hz, 1 H, benzoyloxy-H), 7.77 (s, 2H, arom. H), 7.88 (dd, ^3J = 7.4 Hz, ^4J = 1.4 Hz, 2 H, arom. H), 7.96 (d, ^3J = 7.3 Hz, 2H, Iso-H), 8.06 (s, 1 H, arom. H), 8.11 (s, 1 H, Iso-H); ^{13}C NMR (62.9 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 17.4, 17.9 (CH_3), 22.5, 25.9, 34.9 (Cyh–CH_2), 44.8 (Cyh–Cq), 123.8, 124.4, 125.9, 126.5, 128.4, 129.2, 129.8, 130.7, 133.8 (CH), 128.3, 130.8, 130.9, 134.1, 134.6, 135.8, 147.8, 151.5 (Cq), 164.9, 165.3, 166.5, 166.6 (C=O), 171.6 (COO); FAB-MS: *m/z* = 1025.6 [M$^+$].

Rotaxane 12

68.0 mg potassium carbonate were added to a solution of 51.5 mg (0.19 mmol) 1,4-bis(bromomethyl)benzene **5**, 200.0 mg (0.19 mmol) of the protected tetralactam wheel **10**, 7 mg (0.02 mmol) dibenzo[18]crown-6, and 131.3 mg (0.39 mmol) *p*-tritylphenol **11** in 10 mL chloroform. The mixture was stirred at room temperature for five days. After filtration the organic phase was washed with water several times and dried over magnesium sulphate. The solvent was removed by distillation and purification of the product was achieved by column chromatography; mp 307 °C; R_f = 0.29 ($CHCl_3$/$CH_3CO_2C_2H_5$, 20/1); yield: 116.4 mg (33%); ^{1}H NMR (400 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 1.29 (br, 4 H, Cyh–CH_2), 1.41 (br, 8 H, Cyh–CH_2), 1.68 (s, 24 H, CH_3), 2.10 (br, 8 H, Cyh–CH_2), 4.06 (s, 4 H, OCH_2), 5.95 (s, 4 H, xylene-H), 6.21 (d, 4 H, ^3J = 8.8 Hz, phenoxy-H), 6.81 (s, 8 H, Ar–H), 6.84 (d, 4 H, ^3J = 8.8 Hz, phenoxy-H), 6.92–7.02 (m, 30 H, trityl-H), 7.29 (t, 2 H, benzoyloxy-H), 7.37 (t, 1 H, Iso-H), 7.43 (t, 1 H, benzoyloxy-H), 7.50 (s, 1 H, arom. H), 7.56 (s, 1 H, Iso-H), 7.67 (s, 2 H, arom. H), 7.81 (dd, 2 H, ^3J = 7.7 Hz, benzoyloxy-H), 7.91 (dd, 2 H, ^3J = 7.7 Hz, Iso-H); ^{13}C NMR (100.6 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 18.8 (CH_3), 23.2, 26.6, 35.8 (Cyh–CH_2), 45.6 (Cyh–Cq), 64.6 (trityl-Cq), 70.4 (OCH_2), 113.7 (trityl-CH), 126.3, 126.9, 127.8, 127.8, 127.9, 131.4, 132.8 (CH), 125.5, 127.7, 128.8, 129.0, 130.3, 130.5, 131.2, 131.3, 131.9, 134.5, 134.7, 135.3, 135.4, 136.2, 141.0, 147.0, 148.9, 152.4, 156.2 (Cq), 165.4, 165.7 (C=O), 166.8 (COO); MALDI-MS: *m/z* = 1824.1 [M$^+$ + Na], 1840.3 [M$^+$ + K]; FAB-MS: *m/z* = 1800.0 [M$^+$], 1464.6 [M$^+$ – 1 stopper], 1127.4 [M$^+$ – 2 stopper], 1025.4 [M$^+$ – axle].

Rotaxane 13 with Unprotected Wheel

268.3 mg (0.15 mmol) protected rotaxane **12** were heated in 40 mL dioxane and 20 mL water, with addition of 180.0 mg (3.21 mmol) potassium hydroxide, for eight hours. The solvents were removed by distillation and the residue was dissolved in 2 mL water. With concentrated hydrochloric acid the solution was acidified until pH = 1. The formed precipitate was dissolved in chloroform/ethyl acetate and the separated organic phase washed with water several times and dried over magnesium sulphate. The solvents were removed by distillation and the product was dried at reduced pressure; mp >260 °C; yield: 234.4 mg (93%); ^{1}H NMR (250 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 1.51 (br, 4 H, Cyh–CH_2), 1.61 (br, 8 H, Cyh–CH_2), 1.87 (s, 24 H, CH_3), 2.31 (br, 8 H, Cyh–CH_2), 4.47 (s, 4 H, OCH_2), 6.13 (s, 4 H, xylene-H), 6.41 (d, 4 H, ^3J = 8.8 Hz, phenoxy-H), 7.02 (s, 8 H, arom. H), 7.05 (d, 4 H, ^3J = 8.8 Hz, phenoxy-H), 7.11–7.21 (m, 30 H, trityl-H), 7.42 (s, 1 H, arom. H), 7.46 (s, 1 H, Iso-H), 7.59 (t, 1 H, ^3J = 7.7 Hz, Iso-H), 7.79 (s, 2 H, arom. H), 8.00 (dd, 2 H, ^3J = 7.7 Hz, ^4J = 1.2 Hz, Iso-H); ^{13}C NMR (62.9 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 18.9 (CH_3), 23.3, 26.7, 35.9 (Cyh–CH_2), 45.6 (Cyh-Cq), 64.7 (trityl-Cq), 70.5 (OCH_2), 113.8 (trityl-CH), 118.9, 126.4, 127.1, 127.9, 128.1, 132.0, 132.9, 134.8 (CH), 117.4, 131.4, 135.5, 136.3, 141.1, 147.1, 156.3 (Cq), 159.5 (COH), 167.2, 167.2 (C=O); MALDI-MS: *m/z* = 1718.4 [M$^+$ + Na], 1734.5 [M$^+$ + K].

Rotaxane Assembly 14

9.0 mg potassium carbonate were suspended in a solution of 2.6 mg (0.009 mmol) 1,4-bis(bromomethyl)benzene **5**, 8.6 mg (0.009 mmol) tetralactam wheel **6**, and 30.2 mg (0.018 mmol) rotaxane **13** in 9 mL chloroform. The mixture was stirred for seven days at room temperature. After filtration the solvent was removed by distillation and the crude product was purified by column chromatography; mp > 250 °C; R_f = 0.30 (CH_2Cl_2/$CH_3CO_2C_2H_5$, 10/1); yield: 15.3 mg (39%); ^{1}H NMR (400 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 1.30 (s, 9 H, $C(CH_3)_3$), 1.50 (br, 12 H, Cyh–CH_2), 1.61 (br, 24 H, Cyh–CH_2), 1.80–1.89 (m, 72 H, CH_3), 2.30 (br, 24 H, Cyh–CH_2), 4.20 (s, 8 H, OCH_2), 5.27 (s, 4 H, OCH_2), 6.07 (s, 8 H, xylene-H), 6.14 (s, 4 H, xylene-H), 6.40 (d, 8 H, ^3J = 8.8 Hz, phenoxy-H), 6.96–6.98 (m, 16 H, arom. H), 7.01 (d, 8 H, ^3J = 8.8 Hz, phenoxy-H), 7.08–7.20 (m, 60 H, trityl-H), 7.33–7.34 (m, 4 H, arom. H), 7.38 (s, 2 H, arom. H), 7.45 (t, 1 H, arom. H), 7.56 (m, 2 H, arom. H), 7.71 (s, 4 H, arom. H), 7.72 (s, 2 H, arom. H), 7.86 (dd, 2H, ^3J = 8.8 Hz, arom. H), 8.00–8.03 (m, 4 H, arom. H); ^{13}C NMR (100.6 MHz, $CDCl_3$/CD_3OD, 25 °C): δ = 18.4, 20.7, 30.9, 31.7 (CH_3), 22.8, 23.0,

26.1, 29.2, 29.5, 35.0, 35.2, 35.4 (Cyh–CH_2), 45.0, 45.1 (Cyh–Cq), 64.1 (trityl-Cq), 53.3, 66.9, 69.4, 70.1 (OCH_2), 113.3, 117.5, 125.2, 125.5, 126.0, 126.5, 126.9, 127.4, 127.5, 128.9, 129.9, 130.8, 131.5, 132.4 (CH), 127.1, 130.9, 131.2, 131.3, 134.1, 134.2, 134.3, 134.4, 134.6, 134.7, 134.9, 135.3, 135.7, 135.9, 140.7, 146.5, 148.4, 148.7, 155.7 (Cq), 159.2 (C–O), 165.1, 166.2, 166.4, 166.8 (C=O); MALDI-MS: m/z = 4474.9 [M^+ + Na], 4491.3 [M^+ + K].

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References and Notes

[1] T. Dünnwald, R. Jäger, F. Vögtle, *Chem. Eur. J.* **1997**, *3*, 2043–2051; T. Schmidt, F. Vögtle, *Science Spectra* **1999**, *16*, 58–65; *Molecular Catenanes, Rotaxanes and Knots*, (Ed.: J.-P. Sauvage, C. Dietrich-Buchecker), Wiley-VCH, Weinheim **1999**; G. Schill, *Catenanes, Rotaxanes and Knots*, Academic Press, New York, **1971**; see also: O. Safarowsky, M. Nieger, R. Fröhlich, F. Vögtle, *Angew. Chem.* **2000**, *112*, 1699–1701; *Angew Chem. Int. Ed.* **2000**, *39*, 1616–1618.

[2] D. B. Amabilino, P. R. Ashton, M. Bělohradský, F. M. Raymo, J. F. Stoddart, *J. Chem. Soc., Chem. Commun.* **1995**, *7*, 751–753.

[3] P. R. Ashton, I. W. Parsons, F. M. Raymo, J. F. Stoddart, A. J. P. White, D. J. Williams, R. Wolf, *Angew. Chem.* **1998**, *110*, 2016–2019; *Angew. Chem. Int. Ed.* **1998**, *37*, 1913–1916; Overview on rotaxanes: M. C. T. Fyfe, F. M. Raymo, J. F. Stoddart, in *Stimulating Concepts in Chemistry*, (Ed.: F. Vögtle, J. F. Stoddart, M. Shibasaki), Wiley-VCH, Weinheim **2000**, 211–220.

[4] D. Whang, K. Kim, *J. Am. Chem. Soc.* **1997**, *119*, 415–452; see also: S. R. Batten, R. Robson, in *Molecular Catenanes, Rotaxanes and Knots*, (Ed.: J.-P. Sauvage, C. Dietrich-Buchecker), Wiley-VCH, Weinheim **1999**, 77–106.

[5] E. Lee, J. Heo, K. Kim, *Angew. Chem.* **2000**, *112*, 2811–2813; *Angew. Chem. Int. Ed.* **2000**, *39*, 2699–2701.

[6] C. Gong, H. W. Gibson, *J. Am. Chem. Soc.* **1997**, *119*, 5862–5866.

[7] H. W. Gibson, H. Marand, *Adv. Mater.* **1993**, *5*, 11–21.

[8] Overview: S. Gestermann, R. Hesse, B. Windisch, F. Vögtle, in *Stimulating Concepts in Chemistry*, (Ed.: F. Vögtle, J. F. Stoddart, M. Shibasaki), Wiley-VCH, Weinheim **2000**, 187–198.

[9] The generation number was calculated using the formula described in H. Frey, K. Lorenz, *Chem. unserer Zeit* **1996**, *30*, 75–85. The axle is regarded as the core with the functionality of two and the wheel which presents the branching unit is considered with a functionality of three.

[10] O. Safarowsky, B. Windisch, A. Mohry, F. Vögtle, *J. Prakt. Chem.* **2000**, *342*, 437–444.

[11] G. M. Hübner, J. Gläser, C. Seel, F. Vögtle, *Angew. Chem.* **1999**, *111*, 395–398; *Angew. Chem. Int. Ed.* **1999**, *38*, 383–386; C. Reuter, F. Vögtle, *Org. Lett.* **2000**, *5*, 593–595; R. Shukka, M. J. Deetz, B. D. Smith, *Chem. Commun.* **2000**, 2397–2398.

[12] A. Wissner, M. L. Carroll, K. E. Green, S. S. Kerwar, W. C. Pickett, R. E. Schaub, L. W. Torley, S. Wrenn, C. A. Kohler, *J. Med. Chem.* **1992**, *35*, 1650–1662.

[13] R. Jäger, M. Händel, J. Harren, K. Rissanen, F. Vögtle, *Liebigs Ann.* **1996**, 1201–1207.

[14] F. Vögtle, M. Händel, S. Meier, S. Ottens-Hildebrandt, F. Ott, T. Schmidt, *Liebigs Ann.* **1995**, 739–743; C. A. Hunter, *J. Am. Chem. Soc.* **1992**, *114*, 5303–5311; O. Safarowsky, E. Vogel, F. Vögtle, *Eur. J. Org. Chem.* **2000**, 499–505.

[15] J. De Abajo, E. Guijarro, F. J. Serna, J. G. De la Campa, *J. Polym. Sci., Part A: Polym. Chem.* **1986**, *24*, 483–493.

[16] W. R. Wikoff, L. Liljas, R. L. Duda, H. Tsuruta, R. W. Hendrix, J. E. Johnson, *Science* **2000**, *289*, 2129–2133; V. Balzani, A. Credi, F. M. Raymo, J. F. Stoddart, *Angew. Chem.* **2000**, *19*, 3484–3530; *Angew. Chem. Int. Ed.* **2000**, *39*, 3348–3391.