

## Catenanes, rotaxanes and pretzelanes – template synthesis and chirality\*

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*Abstract:* Catenanes and Rotaxanes of the amide-type have been obtained in remarkable yields via supramolecular template syntheses. The amide-based structures can be designed by appropriate choice of building units. The regioselective synthesis of stable [2]catenane isomers allowed to draw conclusions about their formation. Tetralactams of type **1** act as a host for guests containing amide-units (cf. key-lock intermediate **3**). If the guest molecule is cyclized a catenane is formed while reaction with voluminous stopper groups yield a rotaxane. Rotaxanes can also be synthesized by the ‘slipping method’ in which wheel and axle are heated at about 300 °C for minutes. The formation of rotaxanes containing aliphatic chain axles showed that  $\pi$ – $\pi$ -interactions are not necessary. Introduction of a sulfonamide unit allowed us to do chemistry with catenanes and rotaxanes (cf. **14**, **15**) and furthermore to synthesize topologically chiral species (**15**).

Catenanes and Rotaxanes of the amide type (cf. **4**) can be prepared by using a nonionic supramolecular template effect. The regioselective synthesis of stable [2]catenane isomers allowed us to draw conclusions about their mechanism of formation [1].

### AMIDE-BASED ROTAXANES

Tetralactams of the type **1** form ‘orthogonal key–lock-interactions’ (cf. **3**) with guest molecules containing amide units, which are mainly stabilized by H-bonds. The ‘threading method’ shown in scheme 1 allowed us to synthesize a number of rotaxanes with yields up to 50% [1]. Even rotaxanes holding aliphatic chain axles are formed [2], demonstrating that  $\pi$ – $\pi$ -interactions between host and guest are not necessary. The stopper groups have been varied for new rotaxanes as well [3].

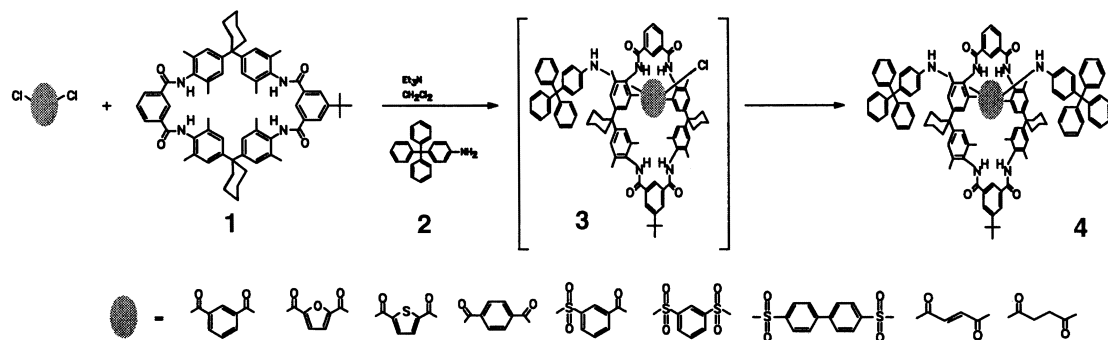
A second method of forming rotaxanes is the ‘slipping process’ [4] in which equal amounts of amide wheel and amide axle are mixed and heated at about 300 °C for 1 min [5]. This method does not need a template assistance which was shown by using a hydrocarbon axle without any amide-bonds (cf. **5**). The stoppers of **5** and the comparison compound **6** having an amide axle were sterically tailored complementary to the wheel in such a way, that they are kinetically stable at room temperature against slipping off. But when heated to 60 °C a deslipping was observed.

Evaluation of the deslipping kinetics showed a significant faster disassembling of the rotaxane **5** compared to **6**, whereas the activation energy for the deslipping reaction was found to be of the same order. We attribute this remarkable fact to the lack of hydrogen bonds between wheel and hydrocarbon axle in rotaxane **5** which causes the wheel to strike more often against the stoppers than in rotaxane **6**, and consequently the statistical probability for the wheel to slip over the hydrocarbon axle’s stoppers is enhanced.

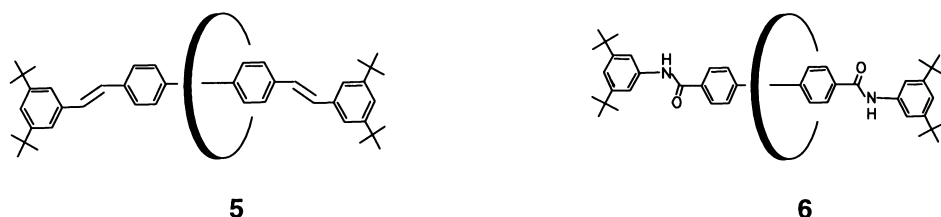
The synthesis of rotaxanes **7–10** containing urea and carbamate units in the axle by a threading

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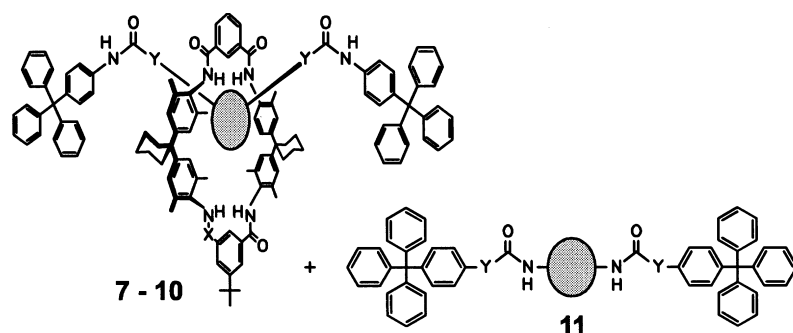
†Corresponding author.



**Scheme 1** Some examples of rotaxanes formed with different acidchlorides.



**Scheme 2** Rotaxanes synthesized by the slipping method.



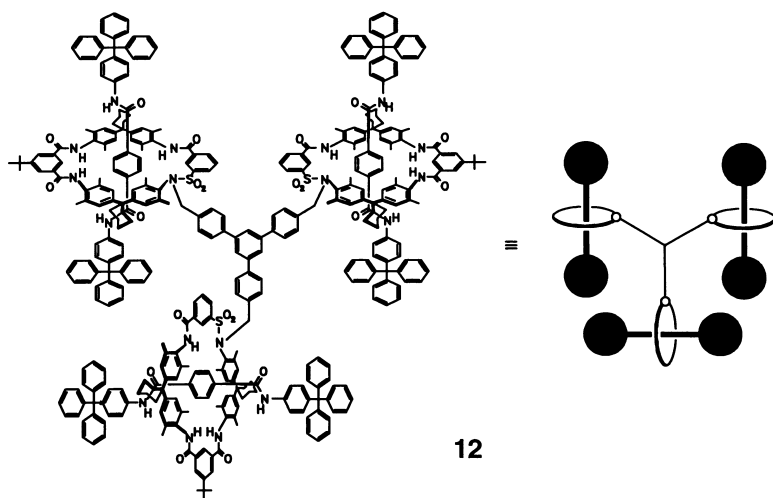
rotaxane	yield	axle	yield	X	Y	
<b>7</b>	4%	--	--	SO <sub>2</sub>	NH	
<b>8</b>	6%	--	--	SO <sub>2</sub>	NH	
<b>9</b>	11%	--	--	CO	NH	
<b>10</b>	24%	<b>11</b>	64%	CO	O	

**Scheme 3** Rotaxanes containing urea and carbamate units.

strategy is possible as well [6]. It allows to create a variety of new rotaxanes by using diisocyanates as guests (Scheme 3).

The formation of these new rotaxanes emphasizes the great tolerance of the template effect between amide-based macrocycles and various guests containing carbonamide bonds.

To investigate the necessity of  $\pi$ - $\pi$ -interactions between the arene units of the host macrocycle **1** and



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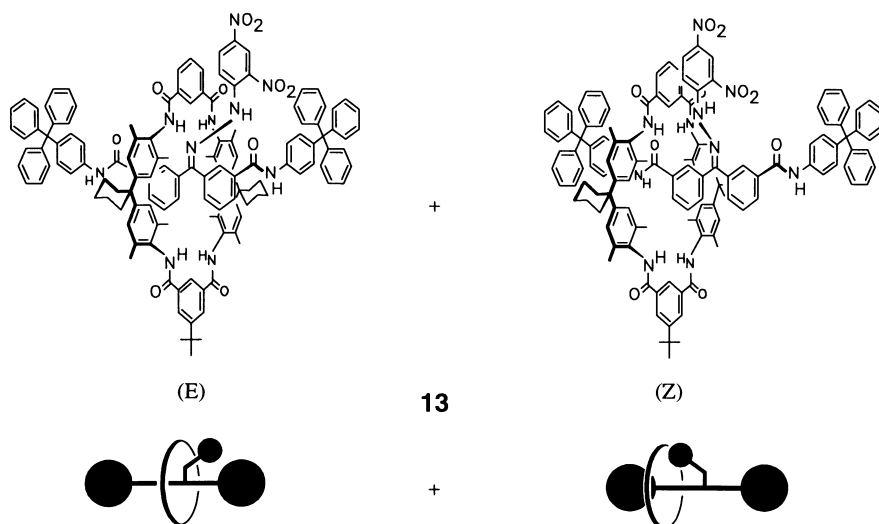
Scheme 4 Tris [2]rotaxane **12**.

the corresponding guest we chose the aliphatic succinyl chloride as potential guest in the synthesis of amide-linked rotaxanes [2]. The rotaxane **4** with partly aliphatic thread was isolated (Scheme 1). These results show that hydrogen bonding is sufficiently efficient for the proposed nonionic template synthesis, even if  $\pi$ - $\pi$ -interactions are negligible.

## CHEMISTRY WITH CATENANES AND ROTAXANES

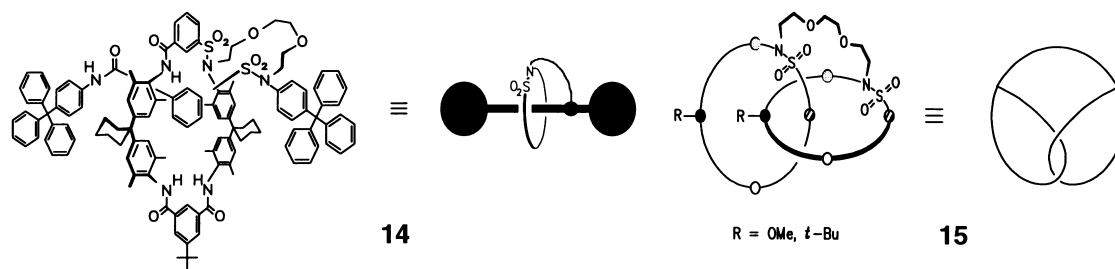
The directed incorporation of sulfonamide groups allowed us to do chemistry with catenanes and rotaxanes [7]. This led to the preparative synthesis of nano-sized rotaxane assemblies, namely the first tris [2]rotaxane (cf. **12**), the first bis [2]rotaxane connected at the axles and the first bis [2]rotaxane with two different axles [8]. The higher acidity of the sulfonamide proton opened up the possibility of chemoselective deprotonation and further alkylation [9]. The rotaxanes were connected with suitable tribromo-, respectively  $\alpha,\omega$ -diiodo compounds.

Furthermore we functionalized the carbonyl group in rotaxanes containing a benzophenone axle (Scheme 5) by the reaction with 2,4-dinitrophenyl hydrazine [10]. We received two isomers of **13**. The derivatisation of the symmetric rotaxane results in a dissymmetrisation. Normally *E*-/*Z*-isomers are the consequence of a dissymmetry by different substituents covalently attached to the C=N-double-bond. In

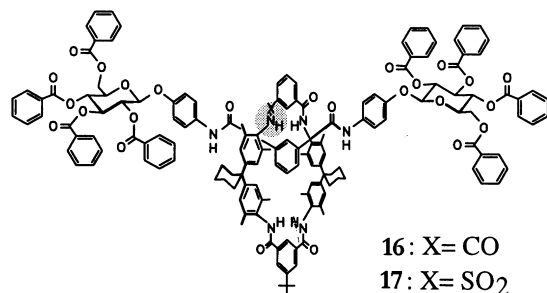


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Scheme 5 Stable *E*-/*Z*-isomers of rotaxane **13**.



**Scheme 6** Topologically chiral '[1]rotaxane' **14** and 'pretzelane' **15**.



**Scheme 7** Rotaxanes with euclidian chiral stoppers.

our case the *E*-/*Z*-isomers of **13** are effected by the mechanically bonded wheel located at one half of the axle.

## CHIRALITY OF CATENANES AND ROTAXANES

The introduction of chirality into mechanically bonded molecules was realized in two ways. On the one hand we synthesized catenanes with sulfonamide groups with a clockwise or anticlockwise fashion. This lead to catenanes with topological chirality [11]. Moreover the introduction of sulfonamide groups allowed us to do chemistry with catenanes and rotaxanes: intramolecular bridging of two sulfonamide groups yields the cycloenantiomeric '[1]rotaxane' (cf. **14**) and the topologically chiral pretzel-shaped molecule **15** ('pretzelane') (12). The separated enantiomers give pronounced Circular Dichroism-curves.

On the other hand 'classic' euclidian chirality has been introduced, too. For the first time (tetrabenzoyl substituted) sugars were used as chiral stopper groups in rotaxanes. The influence of rotaxane formation on chiroptical properties was investigated [13].

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