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Supramolecular Chemistry

Molecular Recognition and Molecular Machines

Two topics of supramolecular chemistry are studied in the Supramolecular Photochemistry group: host-guest complexes based on calixarenes and photoswitchable rotaxanes. – Newly designed calix[4]arenes, substituted with a different number of cycloheptatrienyl or tropylium functions at the upper rim can engender an improvement in the inclusion capability for organic cations, due to an enlargement of the π-basic wall of the host cavity. – Rotaxanes are considered to be prototype molecular machines the »fuel« of which would be light energy at best. Therefore photoactive elements have to be incorporated into such rotaxanes. In order to develop the photo-driven rotaxanes we have chosen as photoreaction the generation of ionic species from neutral precursors. – Actual the first principle investigated is the photoinitiated formation of substituted tropylium salts from arylcycloheptatrienes bearing a leaving group such as the methoxy group.

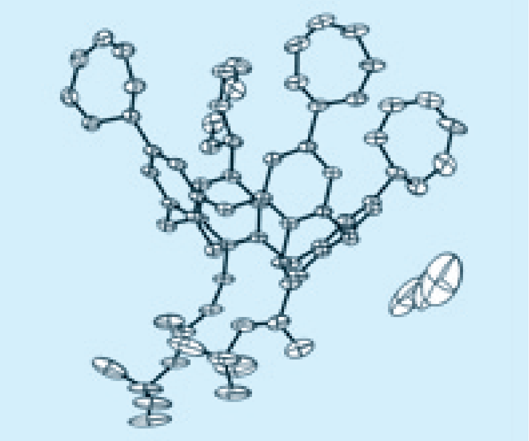


Fig. 1
Crystal structure

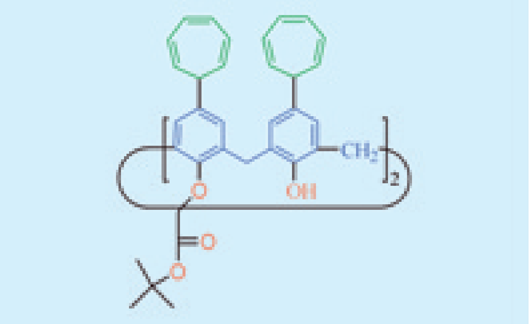


Fig. 2
Chemical structure
A calix[4]arene bearing cycloheptatrienyl substituents at the upper rim

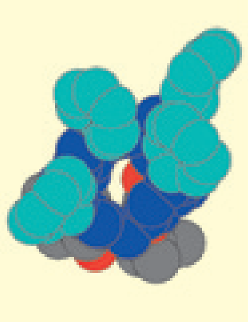


Fig. 3
Calculated structure (MM2)
View into the calix from the upper rim

In the 1980's, a new branch of chemistry, »supramolecular chemistry«, emerged and has expanded very rapidly, particularly in the last 10 years. Supramolecular chemistry is a highly interdisciplinary research field that originated from early ideas on receptors (Paul Ehrlicher), coordination chemistry (Alfred Werner) and the lock-and-key principle of Emil Fischer. It was not until much later on that supramolecular chemistry began to emerge as a discipline by the introduction of concepts such as molecular recognition, preorganization, self-assembly and mechanical binding etc. A widely accepted definition of the word supramolecular is that originating from J.-M. Lehn, one of the 1987 chemistry Nobel laureates, it being: »the chemistry beyond the molecule, bearing on organized entities of higher complexity that result from the association of two or more chemical species held together by intermolecular forces« [1]. In our group, two aspects of supramolecular chemistry are under study:

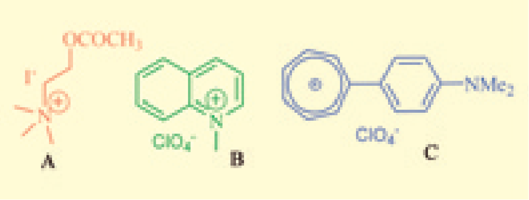
1. Host-guest complexes, based on modified calixarenes as basket-shaped host molecules and different organic cations such as ammonium, iminium and tropylium ions (see below) as guests

The calixarenes are extremely versatile host frameworks; we have modified the upper rim properties of the host by introducing cycloheptatrienyl substituents in order to enlarge the π-basic cavity and to allow the possibility of further property changes by the transformation of the cycloheptatrienyl units into positively charged tropylium ions. Among the calix[4]arenes bearing cycloheptatrienyl groups, the complexation requirements are best matched by hosts with four cycloheptatrienyl groups on the upper rim and two alkyl groups on the lower rim, which are assumed to exhibit a more rigid cone conformation due to intramolecular hydrogen bonds. (Figs. 1–3)

Ammonium ions (in protein side chains) play an important role in molecular recognition in nature and therefore any knowledge regarding the binding of such cations is of interest. Ammonium (A), iminium (B) and tropylium (C) salts were chosen as representatives of three quite different families with respect to their shape and charge distribution. (Fig. 4)

It has been shown that the binding of iminium and tropylium ions by the same host is stronger in lipophilic solvents than that of ammonium ions such as cholin (A) [2]. The positively charged part of the ion penetrates inside the π-basic cavity of the host. It was therefore surprizing to learn that calix[4]arenes with a positively charged tropylium unit at the upper rim are able to bind organic cations much better than

Fig. 4
Three types of organic cations



calix[4]arene without substituents in the upper rim. This means that the inclusion of cationic guests is considerably improved by the presence of the positive charge at the upper rim instead of it repulsing of the cation. (Fig. 5–7)

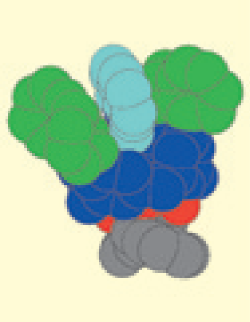


Fig. 5
Calculated structure (MM2) of the complex between a calix[4]arene and the quinolinium ion

2. Rotaxanes incorporating cycloheptatrienyl subunits – towards molecular machines

The concept of machines and motors at the molecular level is old. Our own body can be viewed as a complex ensemble of molecular-level machines that power our motions, repair damage and control our inner worlds of sense, emotion, and thought. Energy transformation and motion in a living cell are based on molecular machines. ATP synthase is certainly the best understood biological rotary motor whilst kinesin and dyenin play an essential role as linear motors in organelle transport along the microtubules in cells and the actin/myosin linear motor is involved in muscle movement. The idea of constructing artificial molecular-level machines, is however a recent one. It was first contemplated in 1959 by Nobel laureate Richard Feynman saying »There's a plenty of room at the bottom« in a talk to the American Physical Society [3]. Although nanometer-level machines already exist and act in the fantasy of science fiction writers (see for example [4]) the construction of artificial molecular machines is in its infancy.

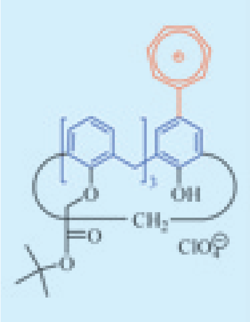


Fig. 6 *(left)*
The organic cation binds …

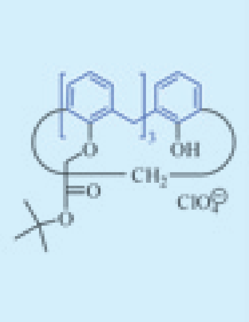


Fig. 7 *(right)*
… does not bind

In principal, there are two different approaches to the miniaturization of useful devices and machines: the large-downward (top-down) approach by photolithography and related techniques which is subject to drastic limitations for dimensions smaller than 100 nm. The alternative strategy is offered by the bottom-up approach, which starts from atoms or molecules and builds up to nanostructures. Chemists do not believe that the »atom-by-atom« bottom-up approach favored by some physicists will be possible. However, chemists are in an ideal position to develop this second strategy for the construction of nanoscale devices and machines. Feynman has outlined this challenge as follows [3]:

»Ultimately, we can do chemical synthesis… The chemist does a mysterious thing when he wants to make a molecule. He sees that it has got that ring, so he mixes

Supramolekulare Photochemie – Molekulare Erkennung und Molekulare Maschinen

Im Arbeitskreis »Supramolekulare Photochemie« werden zwei Aspekte eines Forschungsfeldes bearbeitet, das sich in den letzten 15 Jahren immer schneller entwickelt hat – die supramolekulare Chemie. Darunter versteht man eine stark interdisziplinär geprägte chemische Forschungsrichtung, die die schwache Wechselwirkung zwischen Molekülen zum Inhalt hat und diese nutzt, um Überstrukturen gezielt aufzubauen. Diese Strukturen reichen von Wirt-Gast-Komplexen, die einerseits für die Sensorik eingesetzt werden können und andererseits dem besseren Verstehen der molekularen Erkennung dienen, bis zu Bauelementen für die molekulare Elektronik oder bis zu Maschinen, die auf molekularer Ebene arbeiten.

Wir bearbeiten Calsixarene mit Cycloheptatriensubstituenten als Plattformen für Wirte, die in der Lage sind, organische Kationen einzulagern. Insbesondere Ammonium- und Iminiumionen spielen für die molekulare Erkennung in biologischen Systemen eine große Rolle.

Mit der Synthese und photochemischen Untersuchung von photoschaltbaren Rotaxanen wollen wir außerdem einen Beitrag zur Entwicklung molekularer Maschinen leisten. Neben der aufwändigen chemischen Synthese müssen die Photoreaktionen und die Photophysik der molekularen Schalter, die in die Rotaxane eingebaut werden, studiert werden.

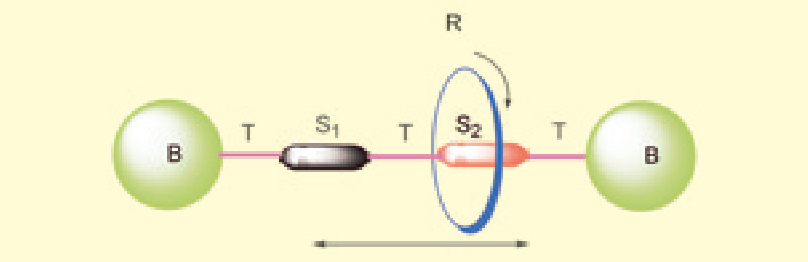


Fig. 8
A two station rotaxane

this and that, and he takes it, and he fiddles around. And, at the end of a difficult process, he usually does succeed in synthesizing what he wants.«

Rotaxanes are considered to be typical prototype molecular machines [5]. These interlocked molecules have a rotor R (a macrocyclic ring) and an axle T (the molecular thread). Two bulky groups B at the ends of the thread prevent separation of the components. (Fig. 8)

The molecular thread and ring must be complementary in that they can interact by attracting forces in order to enable the threading of one component through the ring. Therefore »stations« on both the thread and the ring are necessary to carry the interacting groups of these components, the ring is able to rotate and shuttle along the thread. In order for the rotaxane to approach a molecular motor, the molecular motions that are undirected under the influence of thermal energy must be controlled by external stimuli. Light energy seems to be the best »fuel« for such a molecular machine. Therefore the interacting parts of axle and/or wheel should be photoactive and able to change their properties, which are the basis of the attracting forces. Those forces could be hydrogen bonds, charge transfer interactions, coulomb attraction or repulsion, coordinative bonds etc. If we were to use light energy as a fuel charge transfer interaction then coulomb forces may be especially promising noncovalent interactions that can be controlled by photoreactions.

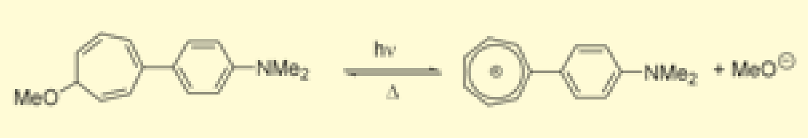


Fig. 9
Photochemical generation of tropylium salts

We have therefore decided to design rotaxanes incorporating subunits that are able to form ions under the influence of light. Cycloheptatrienes can be considered to be candidates for such subunits because they can be transformed into positively charged tropylium ions generating an electron acceptor from an electron donor. Recently we have found that such a transformation is possible with the use of light [6]. (Fig. 9)

The concept:
Assuming that S$_1$ and S$_2$ in the rotaxane shown above are electron donors and S$_2$ is a diarylcycloheptatriene and a stronger electron donor than S$_1$, a ring with acceptor properties will reside mainly on station S$_1$. After irradiation, tropylium ions are formed and the station S$_2$ will be the stronger electron donor. Consequently, the ring will move from S$_1$ to S$_2$. The thermal back reaction between the methoxide ion and the tropylium ion regenerates the starting state.

Realization:
In order to realize the concept, there are two main problems to be solved:

- Design of suitable rotaxanes.
- Investigation of the photoreactions of diarylcycloheptatrienes as model compounds of the corresponding rotaxanes.

We have synthesized various rotaxanes with one and two cycloheptatrienyl stations within a molecular thread [7], the bipyridinium based tetracationic ring was used as electron acceptor component. The following scheme outlines the rotaxane formation that is commonly used in our group. (Fig. 10; Fig. 11).

The above rotaxanes belong to three different prototypes that contain one or two donor stations. In rotaxane II, only one cycloheptatrienyl station is able to bind the tetracationic ring. Therefore, one can study the interaction between the diarylcycloheptatriene subunit and the tetracationic ring with the help of NMR spectroscopy. Two degenerate donor stations present in rotaxane III have shown that there is a fast shuttling process of the ring along the molecular thread. Both rotaxane I and IV contain one diaryl cycloheptatrienyl station and one donor station that is photo-inactive; I and IV are distinguishable by the difference in the donor strength of the second station. One can expect that the ring of rotaxane IV will reside mainly on the cycloheptatrienyl station because the donor strength of the second (xylylene) station is much weaker than the cycloheptatrienyl station. In rotaxane I, it is probable that a shuttling process between the two different stations occurs. However, according to NMR studies of the rotaxane conformation, the ring resides mainly on the aryl cycloheptatrienyl unit as illustrated in the calculated structure below: (Fig. 12)

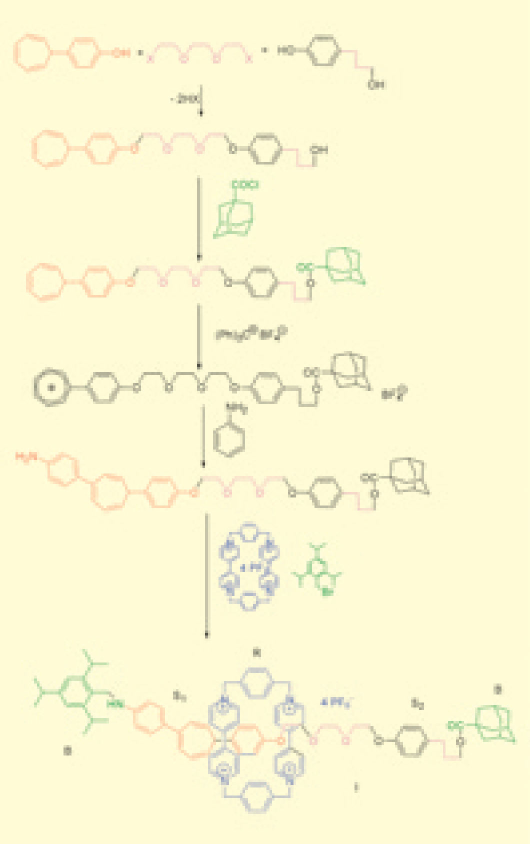


Fig. 10
Synthesis of a two station rotaxane

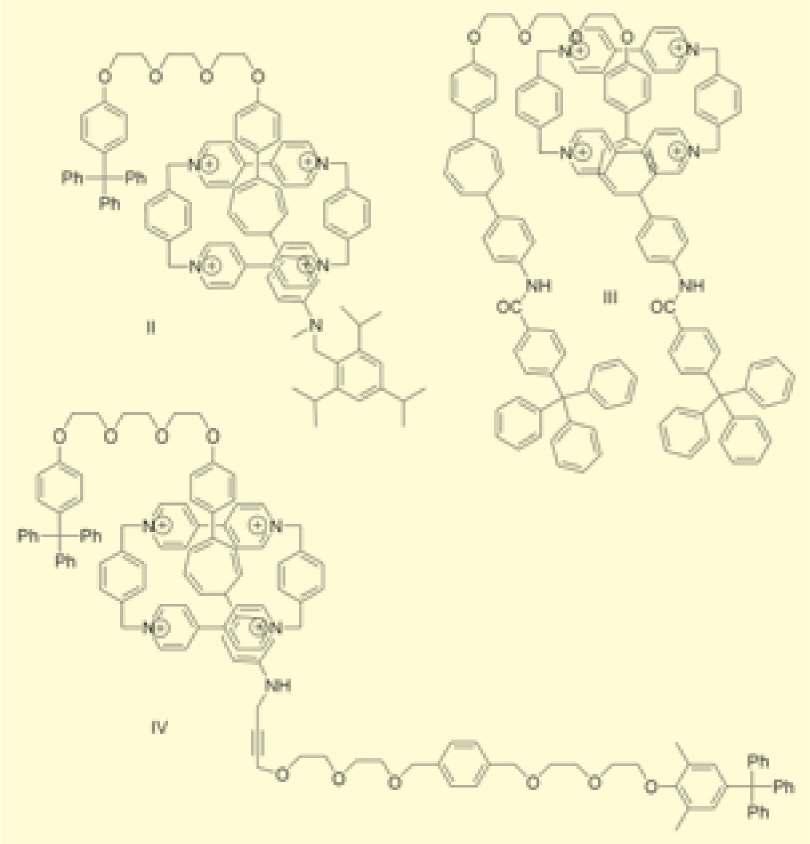


Fig. 11
Three types of rotaxanes

Photoreactivity

Diarylcycloheptatrienes such as compound 1 undergo a 1,7-hydrogen shift as typical reaction in the excited state [8]. (Fig. 13)

This photoreaction is very fast in the parent compound, being complete within ca. 20 femtoseconds (fs); we have found in compound 1 that the reaction is complete within ca. 800 fs. Therefore the question arises as to whether the desired photoheterolysis mentioned above is able to compete with this fast reaction in the excited state. The answer is yes, provided methanol is used as solvent.

Secondly, is there an influence of the acceptor ring in the rotaxane on the photoreactivity of the cycloheptatrienyl subunit? The answer is also yes. Despite the fast photoreaction, the presence of the tetracationic ring controls the direction of the sigmatropic hydrogen shift. In the uncomplexed molecular thread, both possible reaction pathways are observed, in the rotaxane only one reaction direction was observed. (Fig. 14; Fig. 15).

Fig. 12
MM2 structure of the rotaxane I calculated for the gas phase

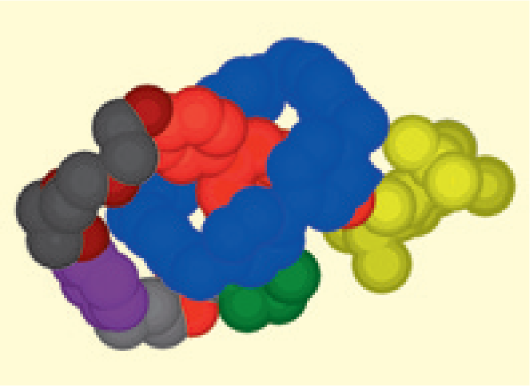
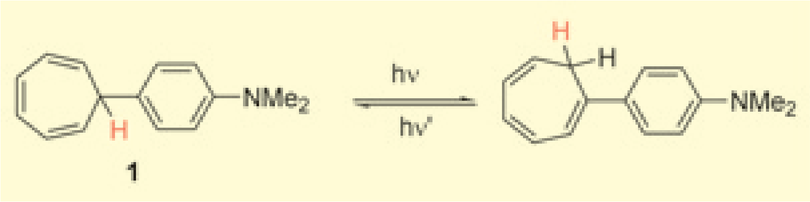


Fig. 13
The reversible sigmatropic hydrogen shift reaction



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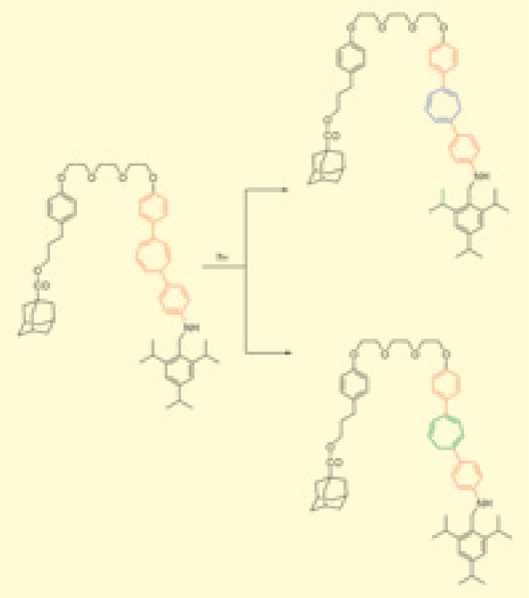

Fig. 14
Photoreactions of the molecular thread

We are studying the photolytic formation of tropylium ions within rotaxanes in order to approach the first step towards a molecular machine, the transformation of light energy into translational movement, however there is a long way to go towards the realization of such a device. Efforts in that direction are in progress in many groups all over the world [5]; however it will inevitably be a long-term project.

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Fig. 15
Photoreaction of the Rotaxane I