Catenanes

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Bridging the Gap: Making the Link in Mechanically Interlocked Chiral Molecules**

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In memory of Christiane O. Dietrich-Buchecker

[n]Catenanes are chains of *n* intertwined rings[1] kept together through a topological link, that is, without any covalent or coordination bonds. The archetype of such molecules is the [2]catenane, in which two rings are mechanically dependent on each other, despite the absence of a bond. These fascinating topological objects can be used as components for nanomachines and nanodevices: the relative motion of the two rings[2] can be controlled by external stimuli such as light, electrons, or metal coordination, and the forward and back processes can be followed by NMR spectroscopy, fluorescence spectroscopy, electrochemistry, or conductivity measurements; circular dichroism spectroscopy can even be used if the catenanes are chiral.

In the history of synthetic catenanes, seminal work by the research groups of Sauvage and Stoddart gave access to catenanes on a preparative scale[1] by using a metal template or donor–acceptor interactions (Figure 1). More recently, catenanes built around multiple hydrogen bonds were described by the research groups of Leigh and Vögtle.[3] Today, the efficiency of such a template combined with electrostatic interactions is at its best with the optically active catenane reported by Furusho and co-workers.[4] For the first time a salt bridge serves as an assembling motif for the formation of [2]catenanes. This amidinium-carboxylate salt bridge template was previously used by these researchers as they have already used it as a recognition motif for the preparation of a family of double-stranded helical polymers.[5] It is very efficient as a template because it exhibits high association constants even in polar solvents and the double hydrogen bond bridge gives a well-defined geometry to the precursor. In addition, the bridge can be opened or closed by varying the pH value of the medium.

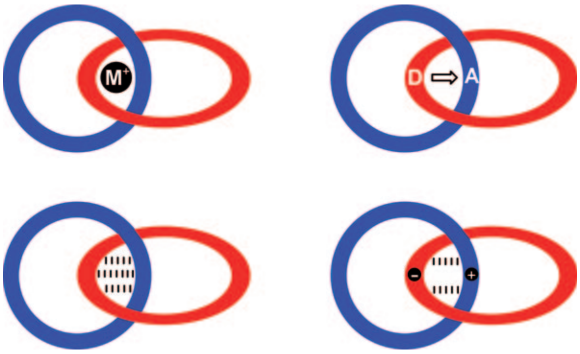

Figure 1. The four different types of templates used for the synthesis of [2]catenanes: metal ion coordination, donor–acceptor interactions, hydrogen bonding, and a salt bridge.

The desired catenane was synthesized in a good 68 % yield by the now famous ring-closing metathesis (RCM) reaction popularized in the field of molecular topology by Sauvage et al.[6] by using the first generation Grubbs catalyst in the double macrocyclization step. Unfortunately X-ray diffraction could not be used to characterize the catenane directly, but unambiguous proof of the catenated structure was obtained by very clever derivatization studies. Indeed, RCM cyclization of the precatenane can not only form the desired catenane but also the two isolated rings or a large [1+1] macrocycle (Figure 2). The authors were able to exclude the possibility of a 1:1 mixture of the two separated rings by comparison of the ^{1}H NMR spectra of the catenane and of an equimolar mixture of the two genuinely synthesized separated rings. To exclude the formation of the large macrocycle they studied the degradation products obtained by a transesterification reaction. A close examination of the ESI mass spectrum clearly proved that the degradation compounds experimentally observed could only arise from the catenated structure as shown in Figure 2. Thus, the amidinium-carboxylate salt bridge has served as an efficient template for the formation of the precatenane, and has been maintained throughout the RCM cyclization step.

Once the catenated structure was proven, the authors studied the possibility to lock and unlock the two intertwined rings. Reaction with trifluoroacetic acid (TFA) unlocks the bridge, thus allowing free rotation of the two rings with respect to one another. Subsequent addition of *i*Pr_2NEt

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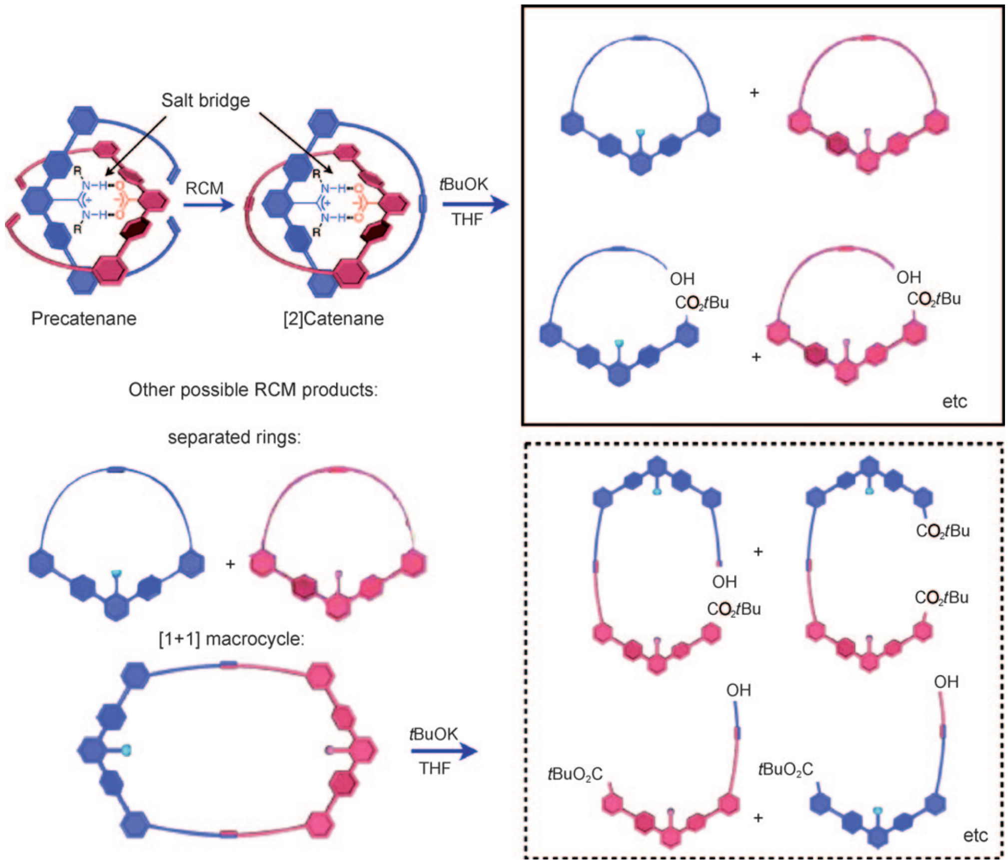

Figure 2. Left: Synthesis of the [2]catenane and other possible RCM products; right: degradative reaction of the [2]catenane and the [1+1] macrocycle by a transesterification reaction with *t*BuOK (Figure adapted from the original one[4]).

restored the salt bridge and the two rings were locked back together. The catenated structure gives extra stability to the system because complete dissociation is impossible: the two rings are always close to each other because of the topology of the molecule. This mechanical link also grants the system a quantitative reversibility; the lock/unlock switch was successfully repeated by the authors.

The [2]catenane obtained by Furusho and co-workers is chiral but not topologically chiral[7] because the chirality does not arise from the orientation of the rings but from the asymmetric carbon atoms present in the amidinium fragment of the backbone. Nevertheless, this mechanically interlocked chiral molecule also allowed the authors to follow the switching by circular dichroism spectroscopy (CD). A strong change in the $\Delta\varepsilon$ value occurred in the 300–350 nm region, which is the signature of a major difference in the relative position of the two rings and the twist of the structure. Alternatively to the acid/base system, the switching of the salt bridge was also with the Zn^{2+}/[2.2.1]cryptand system. In this latter case, the addition of Zn^{2+} ions causes a strong enhancement and a red-shift of the luminescence, while sequestration of the ion by the cryptand returns to the initial state.

Metal and pH value can be seen as two differentiated inputs, while CD and luminescence are two potential independent readouts. Used separately, they can give rise to basic molecular logic gates such as AND, OR, or XOR.[8] Used simultaneously, more complex electronic components such as adders/substractors could be obtained.[8b]

One could also consider this system in terms of molecular nanomachines because the rotation of one part of the molecule relative to the other could be used for simple mechanical applications.[9] With these two mechanically linked rings, the change of geometry between the different conformations is very large, as can be seen from the strong change induced in the CD spectra by the fully reversible switching process. The locking of the salt bridge clearly closes the passage within the rings (Figure 3). This [2]catenane can thus be used as a molecular gate[10] which is locked or unlocked by the pH value. For example, one could imagine this molecule adsorbed on a membrane, and a change in the pH value of the surrounding medium could open the mem-

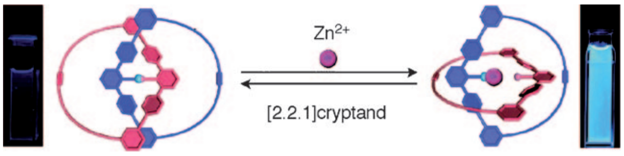

Figure 3. The on/off switching of the salt bridge between the two macrocyclic components by using a Zn^{2+}/[2.2.1]cryptand system; right and left: photos of the solution in a quartz cell with (right) or without (left) coordinated Zn^{2+} under irradiation at 254 nm (Figure adapted from the original one[4]).

brane's pores to let some chemical species go through. Extended to helical polymers, which are a speciality of the research group of Yashima, this change between two extreme conformations could lead to a major variation in the helical pitch and, ultimately, such polymers could be seen as artificial muscles.

In summary, after having unambiguously characterized the catenated structure, Furusho and co-workers used it as a very efficient and reversible molecular switch which can be triggered by external stimuli (zinc coordination or change of the pH value) to control the relative motion of the two macrocyclic subunits. This original catenated structure that bears a salt bridge in its center opens the door to very exciting applications for the construction of more complex nanomachines or nanodevices. A major challenge would be to transfer this system from the solution phase to interfaces or surfaces for electronic or mechanical applications.

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