An Electric Trap: A New Method for Entrapping Cyclodextrin in a Rotaxane Structure

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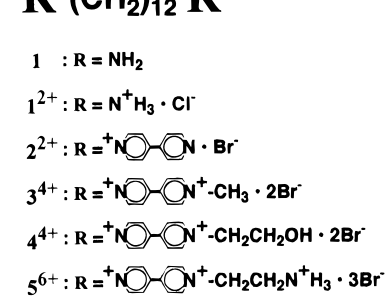
Received December 14, 1999

Recently, much attention has been focused on some interlocked molecules, such as rotaxanes and catenanes, because of their unique structures and properties.[1] Rotaxanes have been prepared by threading a ring onto an axle and then closing the end groups using bulky stoppers[2,3] or by slipping a ring into a dumbbell structure.[4] In either case, bulky stoppers are required for the imprisonment of a ring molecule into a dumbbell structure. Now we have found a new method to entrap a ring molecule on an axle by using repulsive forces between end groups and a ring molecule.

We chose cyclodextrin (CD) as a ring component for the construction of a rotaxane structure because CD has a hydrophobic cavity.[2] A dodecamethylene unit was used as an axle because it can be included in a CD cavity. When α-CD was added to a D_2O solution of dodecamethylenediamine **1**, the ^{1}H NMR spectra showed that the peaks assigned to the methylenes located at the α-, and *β*-positions from both amino end groups shifted to upfield and others shifted to downfield with broadening. This result indicates that there is fast exchange between complexed and free species on the ^{1}H NMR time scale. Addition of α-CD to a D_2O solution of dodecamethylene diammonium dichloride $\mathbf{1}^{2+}$ caused a new set of split signals of each methylene proton along with the original signals, indicating that exchange between complexed and free species is slow on the NMR time scale.[5,6] These results suggest that cations stabilize an α-CD−dodecamethylene chain complex.

If there are some more cations at both chain ends, what will happen? To check the effects of the number of cationic species on the mobility of CD, we studied the complex formation of CDs with $\mathbf{2}^{2+}$, $\mathbf{3}^{4+}$, $\mathbf{4}^{4+}$, and $\mathbf{5}^{6+}$. The ^{1}H NMR spectra of these cationic



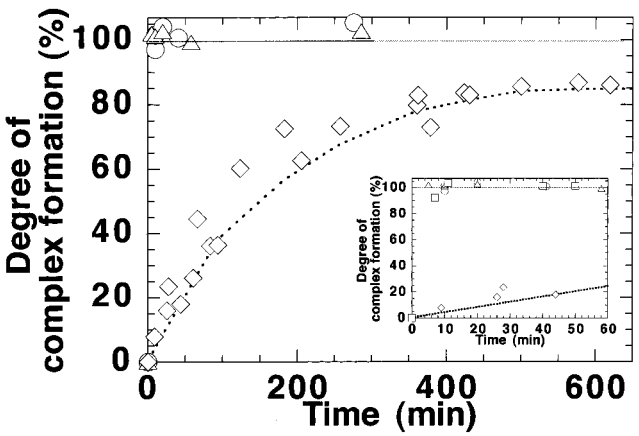


Figure 1. Time dependency of degree of complex formation of $\mathbf{2}^{2+}$(○), $\mathbf{3}^{4+}$(△), $\mathbf{4}^{4+}$(□), and $\mathbf{5}^{6+}$(◇) with α-CD. Degrees of complex formation are calculated from the ratio of the new split ^{1}H NMR signal (complexed species) to the original ^{1}H NMR signal (free species) assigned *d* (*β*-protones in dodecamethylene chain) at alkanediyl compounds (measured in D_2O at 30 °C).

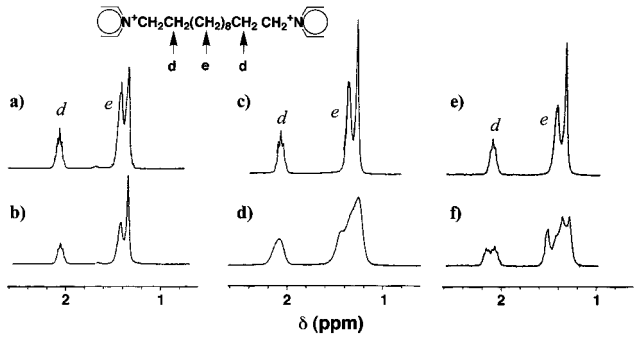


Figure 2. ^{1}H NMR spectra (270 MHz) of $\mathbf{2}^{2+}$ in the absence (a) and presence (b) of *β*-CD, of $\mathbf{3}^{4+}$ in the absence (c) and presence (d) of *β*-CD, and of $\mathbf{5}^{6+}$ in the absence (e) and presence (f) of *β*-CD in D_2O at 30 °C.

α, *ω*-alkanediyl compounds in the presence of α-CD showed new splitting signals, showing that all these cationic α, *ω*-alkanediyl compounds can form stable complexes with α-CD. While we were measuring the ^{1}H NMR spectra of the $\mathbf{5}^{6+}$ in the presence of α-CD, we found that the ^{1}H NMR spectra changed with time. It took a day to reach equilibrium. The mixed solutions of α-CD and other alkanediyl compounds reached equilibrium during sampling for ^{1}H NMR measurements. Figure 1 shows the time course of the degree of complex formation of alkanediyl compounds in the presence of 1.5 M excess α-CD after mixing α-CD solution and the solution of alkanediyl compounds. The degree of the complex formation was calculated from the ratio of the splitting new signal to the original signal. This additional delay of the complex formation between α-CD and $\mathbf{5}^{6+}$ is thought to be caused by the third charge on both end groups, which is the only difference between $\mathbf{5}^{6+}$ and $\mathbf{4}^{4+}$. This result shows multicationic groups inhibit the penetration of α-CD through this cationic group. When the equilibrated solution of $\mathbf{5}^{6+}$ and α-CD was diluted with D_2O, the ^{1}H NMR spectrum did not change for

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10.1021/ja9943647 CCC: $19.00
Published on Web 04/04/2000

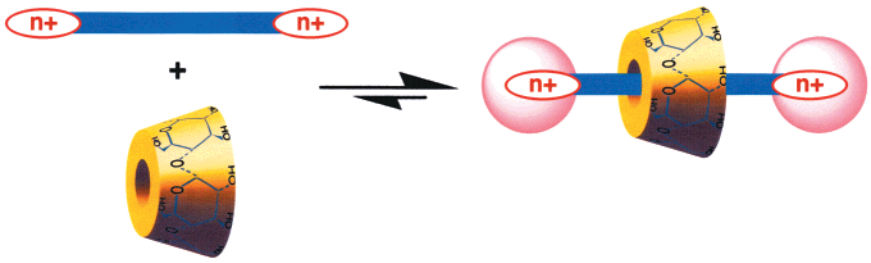

Figure 3. Schematic representation of the rotaxane structure.

several hours, indicating that the rotaxane structure did not change during the period. This result shows multi-cationic groups stabilize the rotaxane structure due to the inhibition of α-CD to come out through this cationic group.

More dramatic effect is observed on the addition of *β*-CD to aqueous solutions of alkanediyl compounds. Figure 2 shows the ^{1}H NMR spectra of $\mathbf{2}^{2+}$ (Figure 2a, 2b), $\mathbf{3}^{4+}$ (Figure 2c, 2d), and $\mathbf{5}^{6+}$ (Figure 2e, 2f) in the absence and presence of *β*-CD. There are no changes in the $\mathbf{2}^{2+}$ methylene signals on the addition of *β*-CD, but methylene signals of $\mathbf{3}^{4+}$ show broadening. Furthermore, methylene signals of $\mathbf{5}^{6+}$ show splitting. Although *β*-CD cannot form a complex with $\mathbf{2}^{2+}$, it can give a complex with $\mathbf{3}^{4+}$ with fast exchange between complexed and free species on the NMR time scale and can form a stable complex with $\mathbf{5}^{6+}$. These behaviors are not due to the steric hindrance of both end groups, because all of these alkanediyl compounds can form complexes with α-CD, but only due to the repulsive interaction between *β*-CD and multi-cationic end groups. On the addition of *γ*-CD, methylene signals of all alkanediyl compounds could not show any changes (data is not shown).

In conclusion, we found that the complexes between CDs and cationic α, *ω*-alkanediyl compounds are stabilized by the increase in the number of cationic species (Figure 3). Thus, multi-cationic groups could be used as a stopper of rotaxane, which is thought to be a novel type of stopper. Now we are studying the complex formation of various multi-cationic α, *ω*-dodecamethylenediyl compounds with CDs and the structures and stabilities of the complexes in detail. The details will be published later.

JA9943647