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Conformational Regulation of Cyclophanes by Formation of Pseudorotaxane Based on a Charge-transfer Complex

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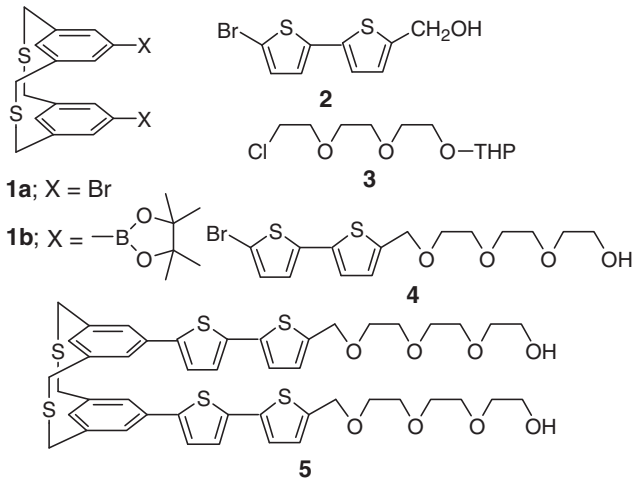
Cyclophanes consisting of diethylene glycol-substituted oligothiophene units as a component have been synthesized. Formation of pseudorotaxane arising from complexation of the cyclophanes and the cyclobis(paraquat-*p*-phenylene) ($CBPQT^{4+}$) has been confirmed. It has also been discovered that conformational properties of the cyclophanes are strongly affected by the formation of pseudorotaxane.

Interlocked molecules such as rotaxanes[1] and catenanes[2] consisting of mobile components have been widely developed due to their various unique chemical and physical consequences. Pseudorotaxanes comprising a linear molecular component encircled by a macrocyclic component have also attracted much attention because their threading and dethreading processes could be conveniently and reversibly controlled, giving the possibility that sophisticated supramolecular devices might be ultimately developed. One of the strategies to create pseudorotaxanes is to form a charge-transfer complex by combination of electron-deficient macrocycles and electron-rich aromatic components. Recently a series of the thiophene-based rotaxane employing cyclodextrin[3] or cyclobis(paraquat-*p*-phenylene) ($CBPQT^{4+}$)[4] as a macrocyclic component have been investigated. There has been a considerable increase in interest in thiophene-based π-conjugated oligomers as advanced molecular electronic materials[5] because of the feasibility in manipulation of their chemical structures.

We have been doing research on small-sized cyclophanes, especially [*n.n*]metacyclophanes in terms of their specific π systems due to the strong transannular π-electronic interactions between the aromatic components in close proximity.[6] These [*n.n*]metacyclophanes can also be characterized by their conformational properties like the conversion between the *syn*- and *anti*-conformers. In the course of our research we have also disclosed unique properties of the [3.3]metacyclophanes consisting of oligothiophene components.[7]

Thus, we have designed a metacyclophane–rotaxane system utilizing the oligothiophene components and $CBPQT^{4+}$ in order to regulate dynamic characteristics of the metacyclophane itself.

Bromocyclophane **1a** was treated with dioxaborolane to give the boronic ester **1b**. Formylation of bithiophene followed by reduction with $NaBH_4$ and successive bromination with NBS afforded the alcohol compound **2** in a yield of 94%. The precursor **4** was obtained by deprotection of the terminal tetrahydropyran (THP) group of the THP-protected diethylene glycol-substituted bithiophene prepared by alkylation of **2** with **3**. The Suzuki coupling between **1b** and **4** using $[Pd(PPh_3)_4]$ as catalyst and Na_2CO_3 as base gave the desired cyclophane having bithiophene units **5** in a yield of 45% (Scheme 1).[8]



Scheme 1. Chemical structures of [3.3]metacyclophane **5**.

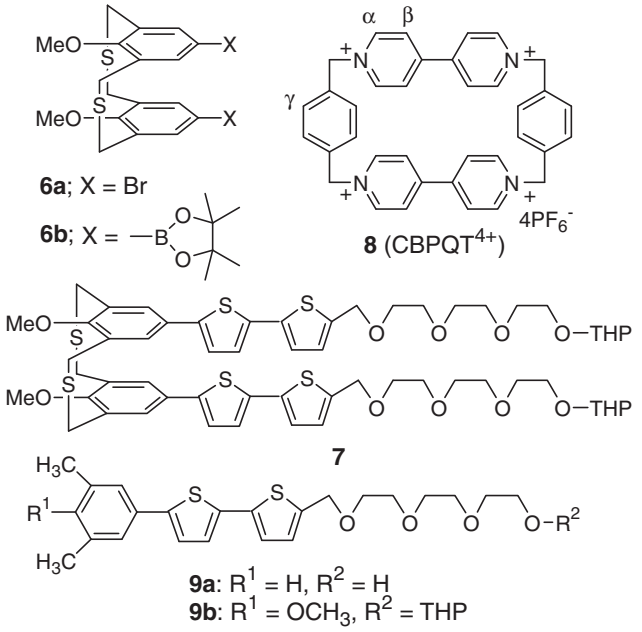
On the other hand, we have reported[7b] that the *syn*-fixed cyclophane **6a** can be isolated from a mixture of the *syn*- and *anti*-conformers after a high-diluted cyclization reaction.

The boronic ester **6b** was prepared by a method similar to **1b**. To achieve a better solubility the Suzuki coupling of **6b** was carried out using the THP-protected diethylene glycol-substituted bithiophene to afford the desired *syn*-fixed cyclophane **7** in a yield of 33% (Scheme 2).[8]

To examine interaction of the two chromophores (bithiophene units) in the cyclophanes, a fluorescence spectral measurement was carried out as shown in Figure 1.

These profiles reflect conformational properties of the cyclophanes. The emission at 418 nm from the monomeric species was observed for **9a**. On the other hand, the cyclophane **7** gave emission at 482 nm from the excimer species due to the *syn*-fixed structure. Although the cyclophane **5** can be considered a flexible structure, a spectrum similar to **7** with a shoulder peak originating from the monomeric emission was obtained. This indicates that the dominant conformer in **5** should be the *syn* one despite its flexible structure recognized on the NMR-time scale.

Addition of $CBPQT^{4+}$ (**8**) to a solution of the cyclophane **5** in CH_3CN induced instantaneous color change indicating the formation of a charge-transfer complex between the electron-rich bithiophene units and the electron-deficient bipyridinium units. This charge-transfer band appeared at 508 nm. The charge-transfer band for **8** and **9a** was observed at 507 nm. Ikeda reported[4a] that the [2]rotaxanes of the bithiophene and terthiophene derivatives with $CBPQT^{4+}$ exhibit their charge-transfer bands at 467 and 507 nm, respectively. From these facts formation of the pseudorotaxane based on the charge-transfer complex has been confirmed in this cyclophane system.



Scheme 2. Chemical structures of [3.3]metacyclophane **7**, **8** and referential compounds.

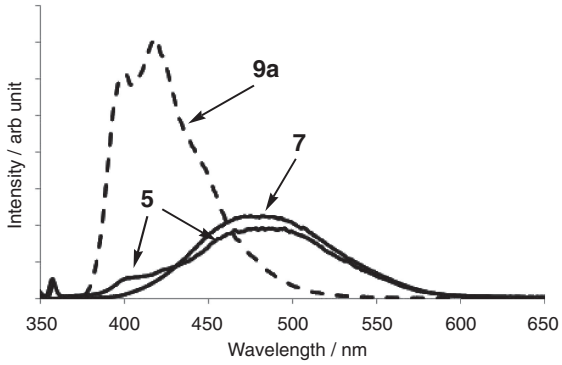


Figure 1. Fluorescence spectra of **5**, **7**, and **9a** in CH_3CN at room temperature. Excitation was performed at 340 nm. The concentration was 1.0×10^{-5}.

Similar experiments were carried out for the cyclophane **7** and the referential compound **9b**. Although the charge-transfer band for **8** and **9b** was observed at 512 nm, the UV–vis spectrum of the mixture of **7** and **8** gave no clear peak with a smaller absorbance than that of **5**.

In order to realize more details about the cyclophane–rotaxane system, ^{1}H NMR spectral titrations of the cyclophane **5** and $CBPQT^{4+}$ (**8**) were carried out as shown in Figure 2.

Figures 2a and 2c show the partial ^{1}H NMR spectra of **5** and **8** in CD_3CN at 298 K, respectively. On addition of a small amount of **8** the ^{1}H NMR spectra (Figure 2b) showed drastic changes. The signals of the free $CBPQT^{4+}$ completely disappeared, meaning fast exchange between the bound and free $CBPQT^{4+}$.

The broadening of the signals for the bithiophene unit of the cyclophane is also observed. Further addition of **8** induces an upfield shift of signals for the bithiophene unit accompanied by

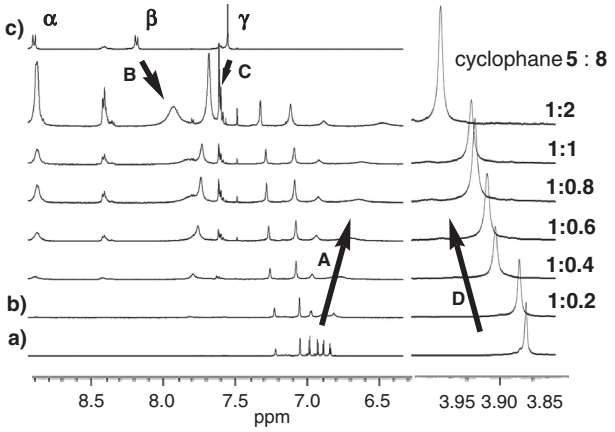


Figure 2. NMR titration of **5** with **8** in CD_3CN at 298 K.

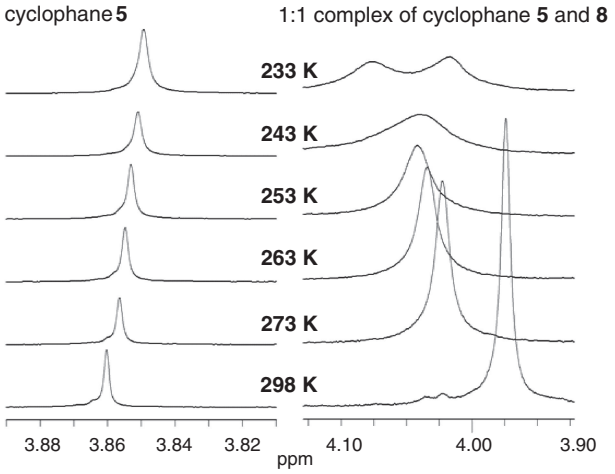


Figure 3. VT-NMR spectra of **5** and 1:1 complex of **5** and **8** in CD_3CN.

broadening, implying the encircling of the bithiophene unit by $CBPQT^{4+}$ ring (arrow A in Figure 2). In the course of addition of **8**, the chemical shift for protons H_α of $CBPQT^{4+}$ is almost identical, whereas the chemical shifts for protons H_β and H_γ move upfield (arrow B in Figure 2) and downfield (arrow C in Figure 2), respectively. These trends indicate that the plane of the bithiophene unit is parallel with the bipyridium unit in $CBPQT^{4+}$ when complexed. A downfield shift of the signal for bridge protons is also observed (arrow D in Figure 2), suggesting that conformational change might occur. A more detail ^{1}H NMR titration[8] was carried out for the rotaxane complex of the cyclophane **5** and **8** to indicate formation of 1:2 complex with the association constants of $5.5 \times 10^6\,M^{-2}$. The referential compound **9a** gave a 1:1 complex with **8** showing the association constant of $2.4 \times 10^3\,M^{-1}$.

In order to understand dynamic behaviors of the cyclophane–rotaxane system VT-NMR was employed as shown in Figure 3.

The signal for the bridge protons in the cyclophane **5** appears at 3.86 ppm as a broad singlet reflecting a flexible structure based on a rapidly equilibrating mixture of the *syn*- and *anti*-conformers. As the temperature was lowered this signal

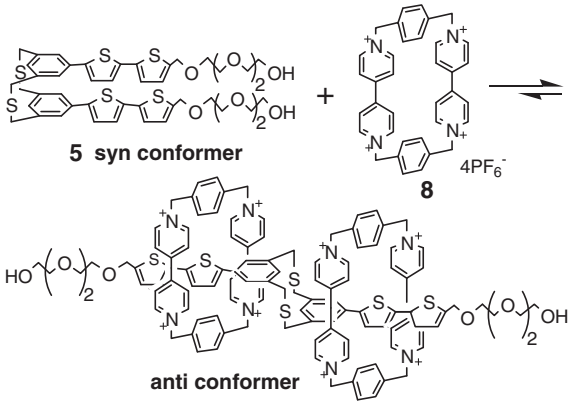


Figure 4. Cyclophane–[2]pseudorotaxane system.

showed a slight upfield shift without broadening. This might be attributable to solvent effects, because other all signals likewise shifted. Such a shift has been often recognized for cyclophane compounds especially using polar solvents on cooling.[6c,6e] On the contrary, the cyclophane–rotaxane system of **5** and **8** shows a slight downfield shift of the signal for the bridge protons when the temperature is lowered. It should be noted that at the lowest temperature a beginning of the splitting is confirmed. These observations strongly suggest that the conformation tends to fix through suppressing the conformational change. With respect to the dithia[3.3]metacyclophane system we have clarified[7b] that the *syn*-conformer and the *anti*-conformer usually have about 1 ppm and about 0.4 ppm separation between two sets of doublets, respectively. Considering the separation between two broad signals the dominant conformer should be *anti* in the cyclophane–rotaxane system. This phenomenon can be explained by steric repulsion between two components of the dithia[3.3]metacyclophane triggered by formation of the pseudorotaxane structure as shown in Figure 4. Obviously the bulky components seem to hinder formation of the *syn*-conformation.

Similar ^{1}H NMR studies were carried out for the *syn*-fixed dithia[3.3]metacyclophane **7**. Contrary to the cyclophane **5**, no disappearance and shift of the signals of **8** are observed on its addition.[8] These results mean that the complexed and uncomplexed species are in relatively slow exchange. In the *syn*-fixed conformation it can be regarded that the threading process can hardly occur because of the two components of the cyclophane existing in close proximity. No conformational change of **7** was recognized. Formation of 1:1 complex with the association constants of $7.9 \times 10^2\,M^{-1}$ was calculated for the cyclophane–rotaxane system of **7** and **8**.

In conclusion we have demonstrated that the conformation of the cyclophanes can be regulated by formation of pseudorotaxane in such a small-sized cyclophane system for the first time. This finding could possibly give a novel aspect on outer stimuli toward dynamic structure of the cyclophane system.

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