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Disparate orientation of [1]rotaxanes

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Abstract—A novel [**1**]**rotaxane 2** has been synthesized employing a 4-methyl-benzenesulfonyl and an azobenzene modified β-cyclodextrin (β-CyD) at the **2** position, through self-inclusion complexation and Suzuki-coupling capping in aqueous solution. Disparate absorption, induced circular dichroism (ICD) properties from its isomer [**1**]**rotaxane 1**, prepared from the isomeric β-CyD modifier at the **6** position, and the photoisomerization of [**1**]**rotaxane 2** were thoroughly investigated.

The design of preparation of molecular machines with controlled motions at the molecular level is essential for the development of future toolbox of nanotechnology. Rotaxanes,[1] in which the relative positions of the interlocked components can be changed in response to an external input and can be capable of varying physical properties, have attracted more and more attention because of their challenging constructions and potential applications in areas such as molecular switches,[2,3] molecular logic gates,[4,5] and memory devices.[6] Cyclodextrins (CyDs) continue to be attractive wheel components in constructing rotaxanes recently.[7] The foundation for the construction of a CyD-based rotaxane is the interactions between the hydrophobic cavity of the CyD and a special hydrophobic unit in the linear component.

Great attention has been given to the CyD-based rotaxanes. So far, there are few reports concerning unidirectional threading,[8] and the reports concerning CyD based unidirectional rotaxanes are rare.[9] Recently, we have reported a unidirectional [**1**]**rotaxane 1** constructed by threading from the narrow rim of the β-CyD cavity,[10] in which β-CyD was firstly modified by 4-indo-phenyl-azo-phenol on the **6** position and then capped by a stopper after its self-complementary. From this point of view, we would like to widen the scope of these works to develop new methods for controlling the orientation of β-CyD when synthesizing [**1**]**rotaxanes** for molecular shuttles. Herein, a new β-CyD-based [**1**]**rotaxane 2** was prepared via the self-complementary of the azobenzene modified β-CyD on the untraditional **2** position and consequent Suzuki-coupling capping in aqueous solutions for the first time (Fig. 1).[11] And its photoisomerization of the novel [1]rotaxane isomer including ^{1}H NMR, absorption and induced circular dichroism (ICD) spectra was thoroughly investigated.

The synthesis and purification of **2-OTs-CD** were conducted as previously reported,[12] which was obtained with an yield of 41% from the sulfonylation of β-CyD with 4-methylbenzene-1-sulfonyl chloride (4-OTsCl).

With a considerable variance from the **6-OTs-CD** and β-CyD, with a solubility of 0.04 and 1.89 g/100 mL in water, respectively, **2-OTs-CD** is much more soluble ($S > 35$ g/mL).[12] Moreover, the absorption and induced circular dichroism (ICD) spectra of **2-OTs-CD** and **6-OTs-CD** in aqueous solution exhibit different signals as shown in Figure 2. Compared with the λ_{max} of **6-OTs-CD** at 227 nm, **2-OTs-CD** shows a similar absorption peak at 222 nm but a blue shift about 5 nm. The ICD spectra of these two modified β-CD derivatives exhibit minus Cotton effects. However, the Cotton effect of **6-OTs-CD** is much more minus than that of **2-OTs-CD**. This is attributed to the different positions of the **Ts** moieties relative to the CyD rings in these two molecules, which coincide with the Kajtar sector rules as reported.[12] Evidently, the disparate solubility in water and spectrum properties above encode the considerable differences of these two β-CyD isomers.

Keywords: Cyclodextrin (CyD); [**1**]**Rotaxane**; Induced circular dichroism (ICD).
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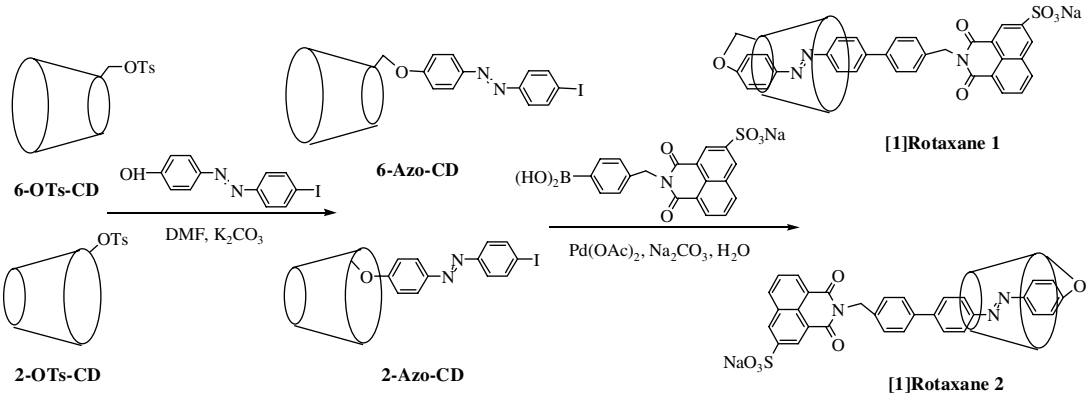

Figure 1. The synthesis of [**1**]**rotaxane 1** and [**1**]**rotaxane 2**.

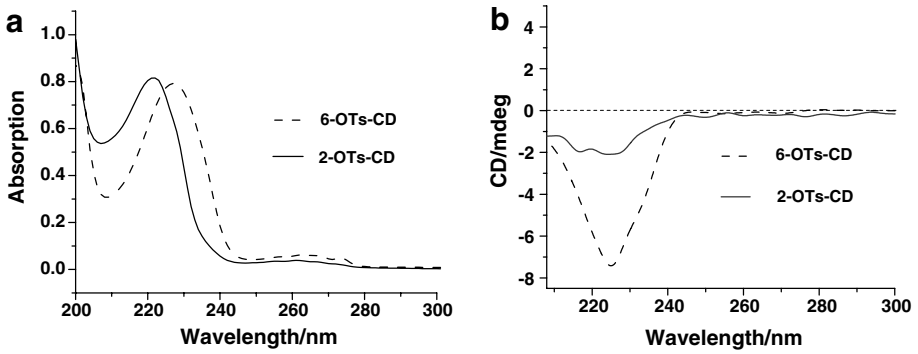

Figure 2. (a) UV absorption (2.5×10^{-5} M) and (b) ICD (2.0×10^{-4} M) spectra of **2-OTs-CD** and **6-OTs-CD** in water at 298 K.

Through the etherification from the different OTs-CD isomers and 4-indo-phenyl-azo-phenol we obtained two azobenzene modified β-CyD isomers (**6-Azo-CD** and **2-Azo-CD**).[13] **2-Azo-CD** was also found to be much more soluble than its isomer **6-Azo-CD** (**2-Azo-CD** is very soluble in water while the latter is just ordinarily soluble in hot water). And their absorption and ICD spectra in aqueous solution are shown in Figure 3. Dissimilar optical spectral properties are also obviously encoding the two isomers. This may be attributed to the different self-inclusion configuration of azo moieties in the CyD cavities between **6-Azo-CD** and **2-Azo-CD** (the angles between the transition dipole moment of the azo groups and the axis of β-CyD cavities are different).

Similar to [**1**]**rotaxane 1**,[10] [**1**]**rotaxane 2** was also prepared conveniently and directly through self-inclusion complexation of **2-Azo-CD** and subsequent Suzuki-coupling capping in aqueous solution.

However, these two isomers have obvious disparate physical and structural properties. [**1**]**rotaxane 2** is provided with a much better water solubility than the other as well as the two derivatives on the **2** position of β-CyD (**2-OTs-CD** and **2-Azo-CD**) mentioned above. And,

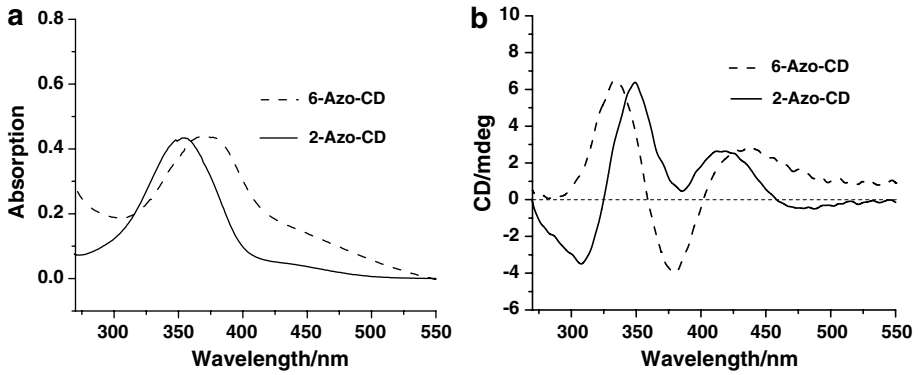

Figure 3. (a) UV absorption (2.5×10^{-5} M) and (b) ICD (2.0×10^{-4} M) spectra of **2-Azo-CD** and **6-Azo-CD** in water at 298 K.

moreover, observed resonance difference occurs between the two [1]rotaxane isomers as indicated (Fig. 4) by ^{1}H NMR spectra in DMSO-d_6 (298 K). The shield effects of CyD rings with reverse orientation engender discrepant chemical shifts to the aromatic protons of the threads. In [**1**]**rotaxane 2,** the ^{1}H NMR signals for H_d, H_e, H_f and H_a of the thread arise downfields by about 0.08, 0.22, 0.15 and 0.03 ppm with respect to the corresponding protons in [**1**]**rotaxane 1**, respectively. The UV–vis spectra and ICD spectra of [**1**]**rotaxane 2** and [**1**]**rotaxane 1** recorded at 298 K in DMSO show similar signals (see Supplementary data, Fig. S1).

The *E*/*Z* photoisomerization reaction of [**1**]**rotaxane 2** in DMSO-d_6 (298 K) is revealed by the corresponding chemical shift changes of the thread protons in ^{1}H NMR spectra (Fig. 5). Irradiation at 365 nm for 3 h leads to several new signals of cis-azobenzene, appearing at $\delta = 6.86$ (H_a), 6.90 (H_d), 7.44 (H_f) and 7.61 (H_e) ppm, correspondingly the initial peaks appearing at $\delta = 7.17$, 7.85, 7.50 and 7.71 ppm, respectively. It is reasonable that the signals of aromatic protons of the azobenzene unit generally shift to upfield upon their isomerization from trans to cis configuration, as a result of the magnetic shielding effect of aromatic rings. Moreover, what should be noted is that H_d in [**1**]**rotaxane 2** was found in an obvious upfield shift of about 0.97 ppm after the irradiated isomerization from the trans conformation to cis, shifting more upfield more than H_d in [**1**]**rotaxane 1** is reported in our previous paper, which shifted upfield about 0.7 ppm.[10] It is reasonable that after the irradiated isomerization from trans to cis, the narrow rim of β-CyD in [**1**]**rotaxane 2** influences much more to the aromatic H_d of the thread than that effected by the evase rim of β-CyD in [**1**]**rotaxane 1**. Integrals of the two signals of H_e appear with about 1:3 ratio (trans to cis), which suggests that at the photostationary state about 75% of ***E***-[**1**]**rotaxane 2** was transformed to ***Z***-[**1**]**rotax-**

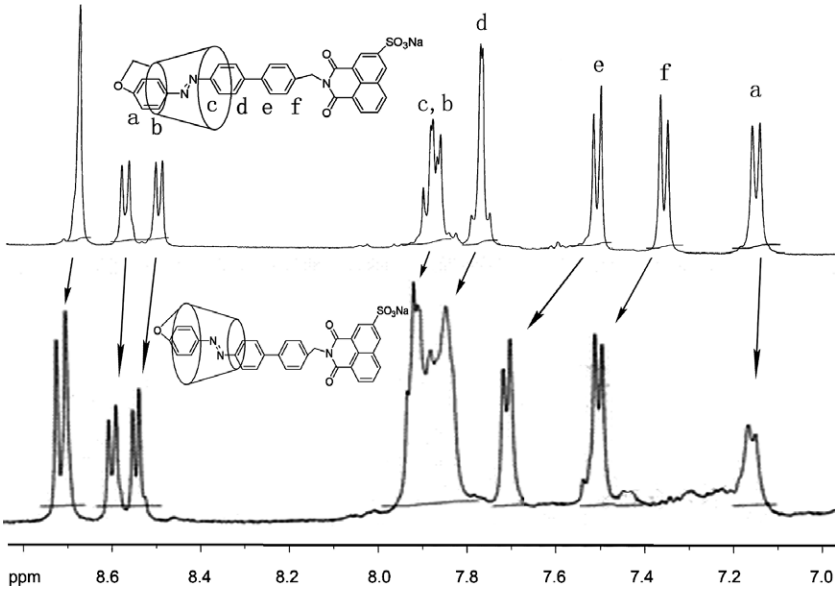

Figure 4. Partial ^{1}H NMR spectra of [**1**]**rotaxane 1** (top) and [**1**]**rotaxane 2** (bottom) in DMSO-d_6 at 298 K.

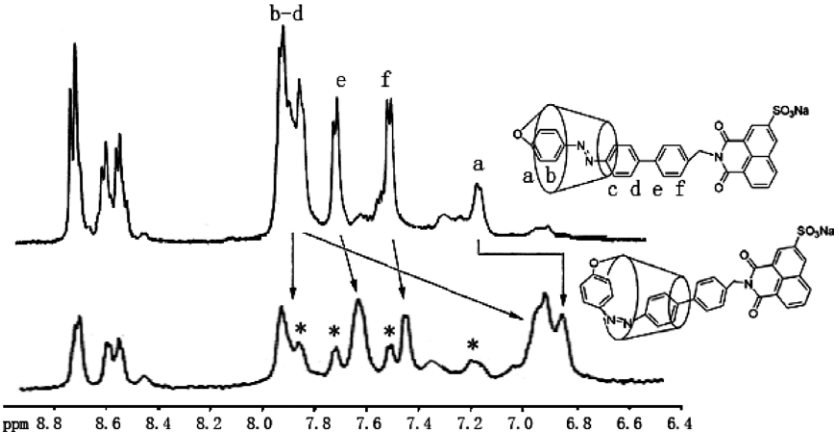

Figure 5. Partial ^{1}H NMR spectra of [**1**]**rotaxane 2** at the original state (top) and at the photostationary state (bottom) after irradiation on 365 nm for 3 h in DMSO at 298 K. (∗ at the bottom stands for the H_d, H_e, H_f and H_a of ***E***-[**1**]**rotaxane 2** without isomerization.)

ane 2 isomer. This isomerization ratio is higher than that of [**1**]**rotaxane 1** (about 50%),[10] which is due to the evase rim of β-CyD in [**1**]**rotaxane 2**, which provides more space for the isomerized *cis*-azobenzene easily than the narrow rim of β-CyD in [**1**]**rotaxane 1**.

On account of the trans–cis photoisomerization of the azobenzene moiety and the subsequent shuttling movement of the β-CyD ring, the shuttles of [**1**]**rotaxane 2** can be confirmed by the varied absorption and ICD spectra. The irradiation on the [**1**]**rotaxane 2** solution at 365 nm for 15 min results in photoisomerization to give a *E*/*Z* mixture, characterized by a slight rise of the absorption at around 292 nm ($\Delta A = 0.21$) and a decrease in absorption at 348 nm ($\Delta A = 0.52$), as well as the presence of an isobestic point at 313 nm (Supplementary data, Fig. S2). Because of good photoreversibility of azobenzene derivative, the photochemical process of the [**1**]**rotaxane 2** system is highly reproducible, and as a result, the photoinduced shuttling motion of the CyD ring can be carried out repeatedly with reversible absorption signal changes.

Temperature increase can induce isomerization of azobenzene from *Z* form to *E* form.[14] UV measurements along with temperature variance of [**1**]**rotaxane 2** show (Supplementary data, Fig. S2) that a gradual increase of the absorption maxima at about 348 nm exists when the aqueous [**1**]**rotaxane 2** was heated from room temperature to 60 and 80 °C. The temperature raise increases the proportion of ***E***-[**1**]**rotaxane 2** in the usual mixture conformation of [**1**]**rotaxane 2**. And the vibrancy of the active β-CyD ring at higher temperature affects the absorption spectra of azobenzene moiety little. The spectra change can be shifted back by natural cooling to room temperature.[7c]

The azobenzene moiety of [**1**]**rotaxane 2** is located in the β-CyD cavity. The ICD spectra with respect to the photoisomerization of aqueous [**1**]**rotaxane 2** (2.0×10^{-4} M) solution (Fig. 6) shows a positive Cotton effect at 423 nm and a weaker negative Cotton effect at 317 nm. After the prolonged irradiation at 360 nm, these two Cotton Effects experience a similar sign of ICD signals but only an intensity increase to the *trans*-azobenzene [**1**]**rotaxane 2**. The ICD spectral changes can be shifted back by irradiation at 430 nm.

Nevertheless, variable-temperature ICD measurements of [**1**]**rotaxane 2** were observed to exhibit a contrary trend. Both the ICD signals at 423 and 317 nm decreased gradually while the aqueous [**1**]**rotaxane 2** was heated from room temperature (25 °C) to 80 °C. And when it was cooled back to room temperature, the changes of the ICD signals were shifted back. This thermosensitive ICD variance was in accordance with other azobenzene-based rotaxanes we reported previously.[7c]

In conclusion, on the basis of the previous work concerning [**1**]**rotaxane 1**, we prepared its isomer, [**1**]**rotaxane 2**, conveniently and directly. Firstly, β-CyD was modified by 4-methyl-benzenesulfonyl chloride on the **2** position and then connected with 4-indo-phenyl-azo-

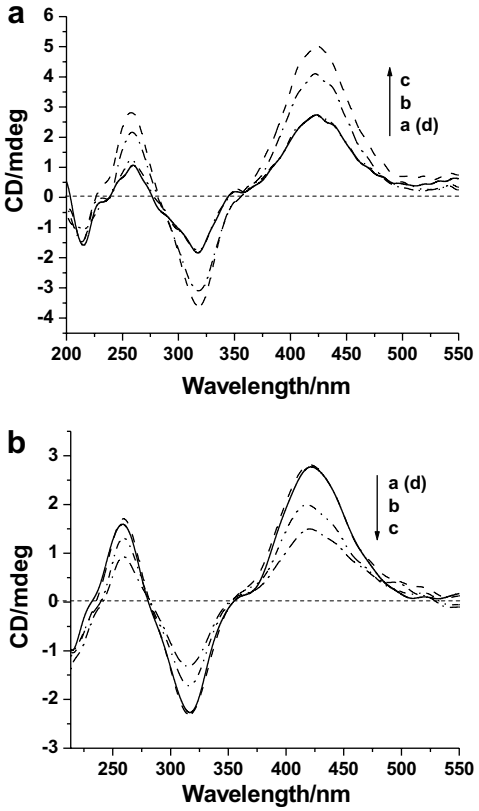

Figure 6. (a) Photoisomeric ICD spectra of [**1**]**rotaxane 2** (25 °C, 2.0×10^{-4} M) after irradiation at 365 nm for 0 min (a), 3 min (b), 15 min (c), the spectra change can be shifted back by irradiation at 430 nm for 15 min (d); (b) variable-temperature ICD spectra of [**1**]**rotaxane 2** (2.0×10^{-4} M) at 25 °C (a), 60 °C (b), 80 °C (c), the spectra change can be shifted back by natural cooling to 25 °C (d).

phenol, the gained **2-Azo-CD** was employed to experience a self-inclusion complexation and Suzuki-coupling capping in aqueous solution to obtain this novel [**1**]**rotaxane 2**. The physical, structural and spectral properties of the β-CyD modifiers and final [**1**]**rotaxane** on the **2** position, **2-OTs-CD**, 2-**Azo-CD** and [**1**]**rotaxane 2**, were found disparate from the corresponding isomers on the **6** position. Specifically, they have a better aqueous solubility, different absorption and ICD curves. The azobenzene based [**1**]**rotaxane 2** can be driven to isomerize reversibly by both light and heating, encoding by obvious chemical shifts in ^{1}H NMR spectra, UV–vis absorption spectra and ICD spectra.

Acknowledgments

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Supplementary data

Synthetic details of the compounds associated with this article, the compared UV–vis spectrum and ICD spec-

trum of [**1**]**rotaxane 1** and [**1**]**rotaxane 2**, photoisomeric and variable-temperature UV absorption spectra of [**1**]**rotaxane 2** can be found in the PDF format. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2007.07.209.

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