



Photoswitching of the association of a permethylated α -cyclodextrin-azobenzene dyad forming a Janus [2]pseudorotaxane[†]

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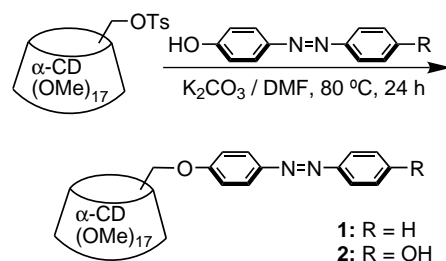
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Abstract—For achieving the on–off operation of the superstructure formation of hermaphrodite cyclodextrin derivatives, we synthesized azobenzene-modified permethylated α -cyclodextrins, **1** and **2**. These compounds formed Janus [2]pseudorotaxanes in CD₃OD–D₂O mixtures. The *E*–*Z* photoisomerization of **1** by UV light irradiation resulted in the dissociation of the superstructure, but, by boiling the solution, the superstructure was recovered through the thermal isomerization of (*Z*)-**1** to (*E*)-**1**. These processes could be repeated many times without any side reactions. This is the first example of the dynamic control of the [2]pseudorotaxane formation of modified cyclodextrins by external stimuli. © 2001 Elsevier Science Ltd. All rights reserved.

Superstructures such as daisy chains formed by the self-association of hermaphrodite molecules have attracted considerable interest from the viewpoint of the assembly of molecular machines.¹ Cyclodextrins (CDs) are particularly convenient scaffolds for constructing the hermaphrodite molecules. Recently, several cyclic *n*-mers of modified cyclodextrins, [*n*]supercyclodextrins^{2b} ([*n*]SCDs), or [*n*]pseudorotaxanes,² and [*n*]rotaxanes,³ have been reported, but hitherto no dynamic control of such superstructures by external stimuli has been attempted.⁴ Here, we report the photodissociation and reassociation of a Janus^{3a} [2]pseudorotaxane.

As the photoreactive hermaphrodite compounds we synthesized **1** and **2**. The desired compounds **1** and **2** were obtained in 76 and 40% yields, respectively, by the reactions of 6-*O*-monotosyl permethylated α -CD⁵ with an excess of 4-hydroxy- and 4,4'-dihydroxy-azobenzenes, in *N,N*-dimethylformamide at 80°C for 24 h (Scheme 1).⁶

An NMR spectrum of a solution of **1** in CD₃OD is shown in Fig. 2(a). The series of permethylated α -cyclodextrin-azobenzene dyads tested so far have always given NMR signals for the cyclic oligomeric species separated from those for the monomeric species because of very slow association–dissociation equilibrium.² The absence of any additional peaks in the NMR spectrum of **1** in CD₃OD means that this compound does not form any oligomers in this solvent. Upon photoirradiation of the solution by UV light⁷ the photoisomerization of (*E*)-**1** to (*Z*)-**1** was observed by the changes in the UV–vis absorption spectrum (Fig. 1) and in the NMR spectrum (Fig. 2(b)), where five sets of new signals (a'–e') were observed after photoirradiation. The product (*Z*)-**1** also absorbs the incident light with a smaller molar absorption coefficient. Therefore, the change in the molar ratio of (*Z*)-**1** to (*E*)-**1** stopped



Scheme 1.

Keywords: azo compounds; cyclodextrins; photochemistry; supramolecular chemistry.

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[†] This paper is dedicated to Emeritus Professor Masazumi Nakagawa on the occasion of his 85th birthday.

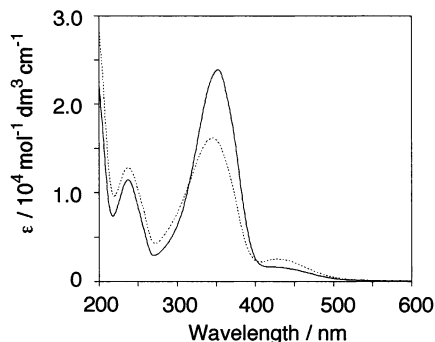


Figure 1. Absorption spectra of **1** (1.08×10^{-4} M) in $\text{CD}_3\text{OD}-\text{D}_2\text{O}$ (1:1) in the dark (solid line) and after photoirradiation (dotted line).

within 15 min, when a photostationary state was reached. At the photostationary state 33% of **1** was transformed into the *Z* form (Table 1). The *Z* form was stable at room temperature for over 24 h. Unfortunately, for compound **2** which showed better solubility to polar solvents and better self-associating ability compared to **1**, the formation of the *Z* isomer upon photoirradiation was not observed. This is probably because the thermal back-reaction starting from (*Z*)-**2** to (*E*)-**2** is very fast.

On using a solvent mixture of higher polarity, $\text{CD}_3\text{OD}-\text{D}_2\text{O}$ (4:1), four sets of new doublets were observed in the NMR spectrum in the dark (*a'*–*d'* in Fig. 2(c)), indicating the formation of a single, symmetrical *n*-mer as a minor species. To determine the association number for the new species, a more polar medium $\text{CD}_3\text{OD}-\text{D}_2\text{O}$ (2:1) was used because of a harmonious balance between the solubility and the intensity ratio of the species to (*E*)-**1**. We obtained the values of $n=1.98 \pm 0.27$ and $K_2=2600 \pm 210$,⁸ and therefore we identified the new species with a [2]SCD or a Janus [2]pseudorotaxane **3**.

Upon photoirradiation of UV light, the signal peaks for [2]SCD disappeared from the NMR spectrum (Fig. 2(d)), and the pattern of the remaining signals was very much similar to that obtained for the photoirradiated CD_3OD solution. The population of each species contained in the solution after photoirradiation was estimated with the NMR peak areas. The results are listed in Table 1. The population of (*E*)-**1** decreased from 70 to 50% upon photoirradiation. This leads to a drastic decrease in the concentration of **3**. (*Z*)-**1** populated 50% after photoirradiation, but no formation of a new associated species was observed in the NMR spectra. This means that (*Z*)-**1** does not form any complex even in $\text{CD}_3\text{OD}-\text{D}_2\text{O}$ (4:1). This is probably because the bent, bulky structure of the (*Z*)-azobenzene moiety prevents the axle from passing through the wheel.

As the solvent polarity became much higher, the *Z* to *E* ratio in the photostationary state became larger. However, as the stability of **3** rose with increasing solvent polarity, the population of **3** increased accordingly.

(*Z*)-**1** was easily isomerized back to (*E*)-**1** by heating the solution nearly up to boiling point for 10 minutes. In the $\text{CD}_3\text{OD}-\text{D}_2\text{O}$ (4:1) solution the recovery of (*E*)-**1** by heating immediately induced the formation of the compound **3**. Thus, the heating triggered the re-associa-

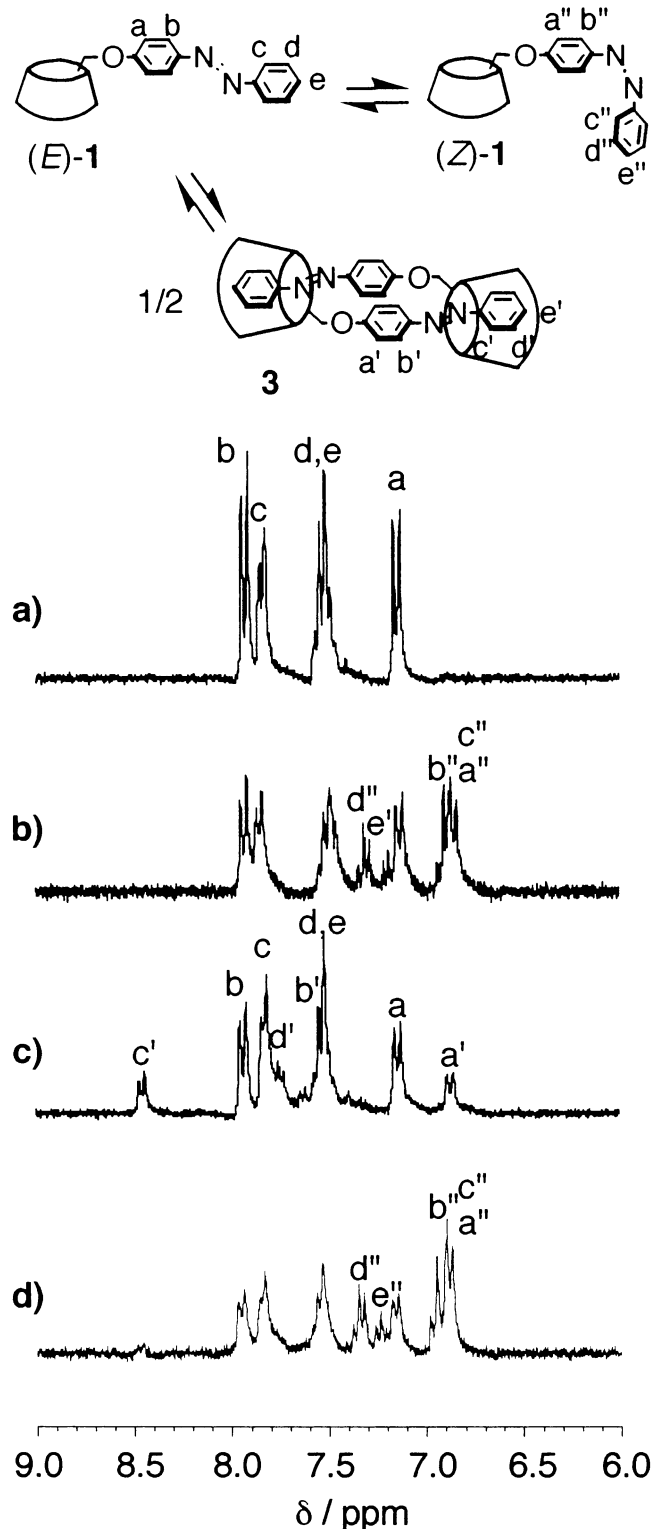
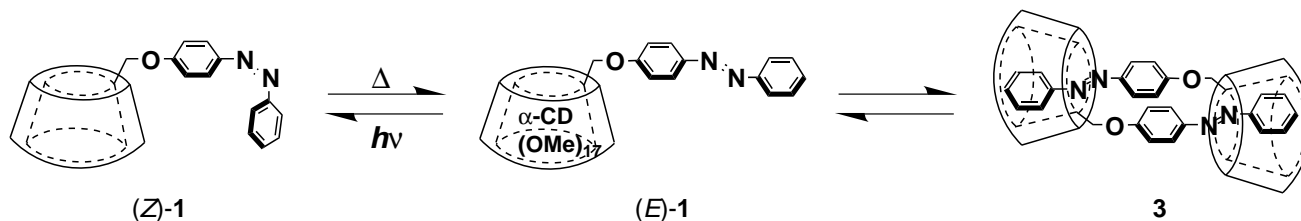


Figure 2. The aromatic region of 270 MHz ^1H NMR spectra of **1**. 5.08 mM in CD_3OD : (a) in the dark; (b) after photoirradiation, 4.07 mM in $\text{CD}_3\text{OD}-\text{D}_2\text{O}$ (4:1); (c) in the dark; (d) after photoirradiation.



Scheme 2.

Table 1. Population of (*E*)-, (*Z*)-**1** and **3** under various conditions^a

Conditions		(<i>E</i>)- 1 (%)	(<i>Z</i>)- 1 (%)	3 (%)
CDCl ₃	Dark	100	0	0
	PS ^b	79	21	0
CD ₃ OD (5.08 mM)	Dark	100	0	0
	PS	67	33	0
CD ₃ OD–D ₂ O (4:1) (4.07 mM)	Dark	70	0	30
	PS	50	50	Trace
CD ₃ OD–D ₂ O (2:1) ^c (<3.39 mM)	Dark	50	0	50
	PS	35	55	9
CD ₃ OD–D ₂ O (1:1) ^c (<2.54 mM)	Dark	27	0	73
	PS	17	60	23

^a Estimated by the NMR method.

^b PS, photostationary state.

^c The exact concentration is not known, because of precipitates formed during the measurement.

tion of **1**. By repeating photoirradiation and heating alternately the dissociation and re-association of **1** was achieved nearly endlessly without any side reactions (Scheme 2).

In conclusion, the compounds **1** and **2** in CD₃OD–D₂O mixtures formed Janus [2]pseudorotaxanes or [2]SCDs. A substantial portion of the [2]SCD **3** was destroyed upon irradiation of UV light. The [2]SCD was recovered by heating the solution. This finding will contribute to development of ways to control the supramolecular structures by external stimuli.

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- Compound **1**: yellow solid, mp 238–240°C. Anal. found: C, 55.55; H, 7.86; N, 2.01%. Calcd for C₆₅H₁₀₂O₃₀N₂·H₂O: C, 55.38; H, 7.44; N, 1.98%. MALDI-TOF-MS (*m/z*): 1415 [M+Na]⁺. ¹H NMR (270 MHz, CDCl₃, 23°C): δ 7.92 (d, *J*=9.18 Hz, 2H, Hb), 7.86 (d, *J*=6.75 Hz, 2H, Hc), 7.49–7.43 (m, 3H, Hd, e), 7.07 (d, *J*=9.18 Hz, Ha), 5.11–4.99 (m, 6H, CD-H1), 4.47–3.05 (m, CD-H). Compound **2**: orange solid, mp 144–146°C. Anal. found: C, 53.21; H, 7.08; N, 2.13%. Calcd for C₆₅H₁₀₂O₃₁N₂·3H₂O: C, 53.40; H, 7.08; N, 2.13%. MALDI-TOF-MS (*m/z*): 1431 [M+Na]⁺. ¹H NMR (270 MHz, CDCl₃, 23°C): δ 7.95 (s, 1H, Ar-OH), 7.78 (d, *J*=8.90 Hz, 2H, Hb), 7.71 (d, *J*=8.90 Hz, 2H, Hc), 6.97 (d, *J*=8.90 Hz, Ha), 6.87 (d, *J*=8.90 Hz, 2H, Hb), 5.05–4.92 (m, 6H, CD-H1), 4.43–4.30, 4.01–3.99, 3.80–3.05 (m, CD-H).
- Photoirradiation was performed with a high-pressure mercury arc lamp equipped with a CuSO₄ aqueous solution filter for isolating the light of 366 nm.
- Association constant *K_n* was determined assuming that monomers M associate to form a single *n*-mer M_{*n*}.

$$nM \xrightleftharpoons{K_n} M_n$$

$$K_n = ([M]_0 - [M]) / n[M]^n$$

where *n* is the association number, [M] is the monomer concentration, and [M]₀ is the initial concentration of the monomer. The following three sets of the parameters (*C*₀/mM, *I_x*, *I_y*) reported in Ref. 2b were used: (1.2, 1.38, 2.86), (0.6, 9.1, 11.5), and (0.3, 6.8, 6.0).