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Supramolecular Photochirogenesis with Cyclodextrin–Silica Composite. Enantiodifferentiating Photocyclodimerization of 2-Anthrancenecarboxylate with Mesoporous Silica Wall-Capped γ-Cyclodextrin

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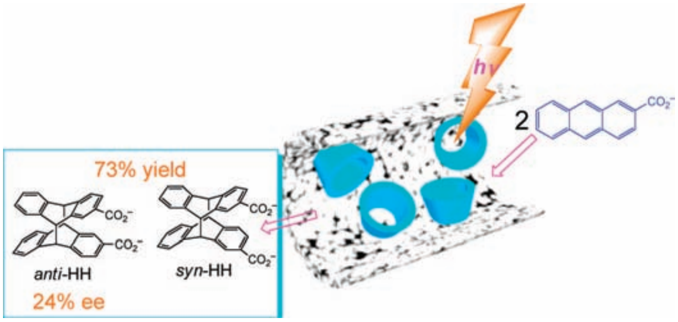
ABSTRACT



γ-Cyclodextrin (CD) immobilized on a mesoporous silica wall to cap one of the CD portals switched the product distribution of photocyclodimerization of 2-anthrancenecarboxylate from head-to-tail to head-to-head with a significant enhancement of the enantiopurity of the chiral head-to-head product.

Asymmetric synthesis is a hot topic in current chemistry because of its contribution to pharmaceutical and fine chemical industries, as well as its application to various optical materials. In sharp contrast to the significant success in asymmetric synthesis in the ground state, its photochemical counterpart remains one of the most challenging and intriguing issues for chemists.[1,2] Asymmetric photosensitization[3] and supramolecular photochirogenesis[4] appear to be highly

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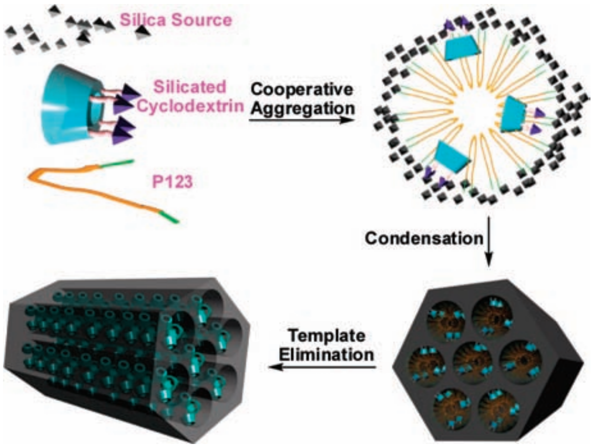
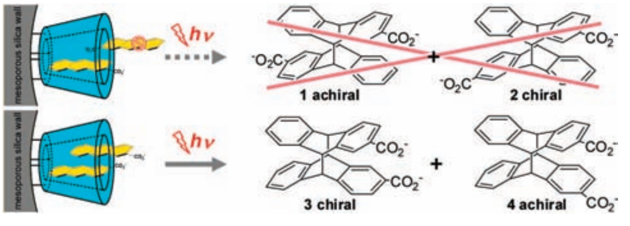
Scheme 1. Synthesis of γ-CD-Modified Mesoporous Silica



promising for efficient chiral induction in photoreactions. For an ideal photochirogenic reaction, the chiral source should efficiently deliver its chiral information to the photosubstrate during the stereodifferentiating process in the excited state and, especially from the industrial and economical standpoints, be readily recyclable for further use. For this purpose, we prepared a new inorganic−organic composite, in which γ-cyclodextrin (CD) is tethered to the channel of mesostructured silica (Scheme 1). Photoreaction in this supramolecular host-based mesoporous silica showed intriguing properties that are markedly different from those of γ-CD in solution or of intact mesoporous silica.

Scheme 2. Photocyclodimerization of 2-Anthrancenecarboxylate with γ-CD Tethered to a Mesoporous Silica Wall



CDs have been frequently employed as chiral hosts in supramolecular photochirogenesis because of their versatile ability to bind various organic guests, ready availability, and inherently chiral nature.[5−9] Recently, we have reported the enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylate (AC) catalyzed by native γ-CD, which yields head-to-tail (HT) dimers **1** and **2** (Scheme 2) as major products.[6] Chemical modification of the γ-CD rim can alter the selectivity to give higher yields of head-to-head (HH) dimers **3** and **4**.[10−12] The orientation of AC molecules inside the cavity can be manipulated by the positively charged groups on the γ-CD rim through electrostatic interactions.[10,11] However, such a modification is not enough to prevent the formation of HT dimers, and the HH cyclodimers were given in only poor yield in aqueous solution.

Mesostructured silica, possessing size-tunable pores (2−50 nm) of high surface area and large pore volume, is a promising candidate for scaffolding catalyst.[13−16] CD modified with active alkyloxysilane groups can be tethered to the mesoporous silica wall.[17−20] We believe that the silica wall will effectively block one of the CD portals, allowing penetration of AC molecules only from the opposite side of the wall.[21−23]

Herein, γ-CD with four triethoxysilane substituents on the primary rim (γ-CD-Si(4); see Supporting Information) was covalently linked to the pore wall of surfactant-templated mesoporous silica by co-condensation with the silica precursor (Scheme 1). The use of the triblock polymer $EO_{20}PO_{70}EO_{20}$ (P123) enabled an efficient introduction of γ-CD on the mesopore wall surface due to possible inclusion by the γ-CD cavity.

In a typical synthesis of the γ-CD-modified mesoporous silica, 0.50 g of P123 and 0.10 g of aqueous HCl solution (35% w/w) were dissolved in 19.90 g of deionized water with stirring at room temperature in 2 h. Then, 1.00 g of tetraethoxysilane and 0.64 g of γ-CD-Si(4) (50% w/w) in DMF were added with stirring in 10 min. The resulting mixture was kept still at 35 °C for 1 week. The white precipitate obtained was separated by filtration and dried at 40 °C. The organic template (P123) was removed by extraction in a diluted HCl/EtOH (1:100 v/v) solution for

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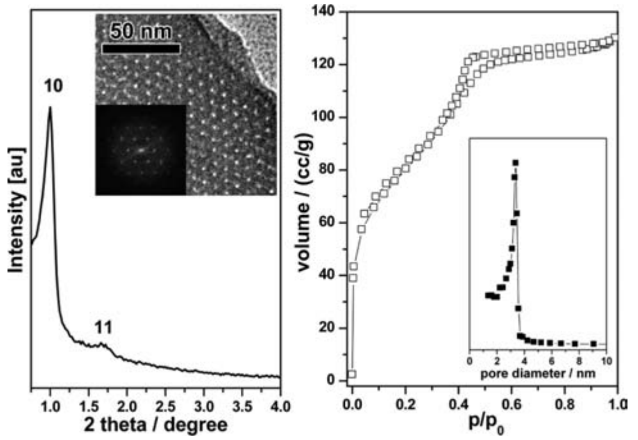

Figure 1. Left: XRD pattern of the extracted γ-CD-modified mesoporous silica. The inset is the HRTEM image and SAED pattern. Right: N_2 sorption isotherms and pore size distribution of the sample (inset).

24 h. For control experiments, mesoporous silica without γ-CD modification was synthesized by the same procedure except for the addition of γ-CD-Si(4). The post synthesis method was also employed to prepare γ-CD-modified mesoporous silica. In a typical postsynthesis, 0.11 g of the above unmodified mesoporous silica material was dispersed in 40 mL of dry DMF followed by an addition of 0.48 g of γ-CD-Si(4) (50 wt % in DMF). The mixture was stirred at 70 °C under nitrogen for 24 h. The solid product was separated by filtration and dried at 40 °C.

As shown in Figure 1, the X-ray diffraction (XRD) pattern of the extracted sample revealed two well-resolved reflections in the range $2\theta = 0.8-2.5°$, which can be indexed as 10 and 11 reflections of a 2D-hexagonal structure. This was also confirmed by the high resolution transmission electron microscope (HRTEM) image and corresponding selected area electron diffraction (SAED) pattern (Figure 1, inset). The extracted material exhibited a typical type IV isotherm with a high sorption amount and a capillary condensation step in a relative pressure range of 0.4−0.5. The BET surface area of this sample was 287.6 m^2/g, and the total pore volume was 0.201 cm^3/g. The pore size distribution calculated from the desorption branch of the isotherm by using the BJH method gives an average pore size of 3.4 nm.

The chemical structure of the γ-CD-modified mesoporous silica was studied by solid-state ^{13}C magic-angle spinning (MAS) NMR spectroscopy. The spectrum of the extracted sample (Figure 2) reveals that the template (P123) is efficiently removed. The urethane carbon (O**C**ONH) is found at δ 159, the γ-CD carbons at δ 60−110, and the trimethylene carbons (OCONH**C**H$_2$**C**H$_2$**C**H$_2$Si) at δ 9−50. This indicates that γ-CDs were well-fixed to the pore walls after the removal of the template. Thermogravimetric (TG) analyses revealed a high loading (25% w/w) of γ-CD in the extracted sample. Combined with the BET surface area, it can be calculated that there is about one γ-CD molecule per 6 nm^2 on the channel surface of the mesoporous silica framework. This means that the mesopore wall is two-fifths-covered with γ-CD, as the van der Waals footprint of γ-CD is ca. 2.3 nm^2.

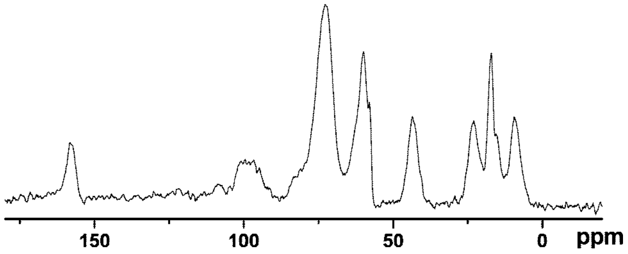

Figure 2. Solid-state ^{13}C MAS NMR spectrum of the extracted γ-CD-modified mesoporous silica.

The photocyclodimerization of AC was carried out in the solid state after an effective inclusion of AC in the γ-CD-modified mesoporous silica in aqueous solution. Typically, to a 5 mL aqueous phosphaste buffer solution (pH 9.0) was added 20 mg of γ-CD-modified mesoporous silica. The mixture was vigorously stirred at room temperature for 2 days in the dark. About 21−28% AC was adsorbed by mesoporous silica materials as estimated by comparison of the UV−vis spectra before and after the addition of mesoporous silica. Though it is difficult to precisely estimate the ratio of AC included within γ-CD cavity among those absorbed in mesoporous silica, the hydrophilic property of mesoporous silica surface and strong binding affinity of γ-CD ($K_1 = 161\ M^{-1}$, $K_2 = 38\,500\ M^{-1}$ at 25 °C)[6] for AC implies that the major part of AC in mesoporous silica should exist in the cavity of γ-CD. The reaction mixture was then centrifuged, and the solution phase was decanted. The white solid obtained was subjected to the photolysis at 360 nm for 15 h with the powder being frequently stirred. The photoproducts and remaining AC were extracted by a phosphate buffer solution at pH 11, and the extract was analyzed by chiral HPLC for the product distribution and the enantiomeric excess (ee).

As shown in Table 1, the photodimerization of AC in the presence of native γ-CD in aqueous solution afforded HT dimers **1** and **2** as major products (89% combined yield), with ee's of 41% for **2** but only 2% for **3**. In keen contrast, the irradiation with γ-CD-modified mesoporous silica gave HH dimers **3** and **4** as major products in 73% combined yield; in particular, the yield of **3** was significantly enhanced from 7% to 45%. The high HH preference indicates that the capping with silica wall facilitates the penetration of AC from the same portal of the CD. This may be rationalized in terms of the modified microenvironment around γ-CD. Since one of the γ-CD portals is fully covered by silica wall, AC molecules enter the γ-CD cavity only through the opposite portal from the more hydrophobic head (aromatic) group of AC (Scheme 2). This leads to a high preference for the HH-oriented 1:2 complex inside the cavity, as the HT complex is dynamically more hindered and thermodynamically less stable as a result of the silica-capped primary portal and the hydrophobic nature of CD cavity. Consequently, the pho-

Table 1. Supramolecular Photocyclodimerization of 2-Anthracenecarboxylate (AC)

			relative yield (%)[b]				% ee[b,c]		
host[a]	phase	conversion (%)	**1**	**2**	**3**	**4**	**2**	**3**	HH/HT[d]
γ-CD	solution[e]	*f*	43	46	7	5	41	−2	0.13
	solid[g]	*f*	26	11	28	35	6	−5	1.7
MS	solid	21	17	15	36	32	3	2	2.1
γ-CD-MS	solid	82	11	16	45	28	6	24	2.7
γ-CD-MS-P	solid	31	18	24	30	29	16	15	1.4

[a] γ-CD: native γ-CD; MS: mesoporous silica; γ-CD-MS: γ-CD-modified mesoporous silica prepared by direct synthesis method; γ-CD-MS-P: γ-CD-modified mesoporous silica prepared by post synthesis method. [b] Relative yield and ee were determined by chiral HPLC equipped with a tandem column of Inertsil ODS and Daicel Chiralcel OJ-R; error in yield 1%; error in ee 2%. [c] The positive/negative ee sign corresponds to an excess of the first/second-eluted enantiomer, respectively. [d] HH/HT = [**3** + **4**]/[**1** + **2**]. [e] In aqueous solution at 0 °C; data from ref 6. [f] Not reported or determined. [g] Solid-state photocyclodimerization of AC-γ-CD complex prepared by mechanically grinding a 1:1 mixture of AC and γ-CD with a mortar and pestle.

tocyclodimerization of AC by silica wall-capped γ-CD predominantly yields the HH products.

Intriguingly, the absolute configuration of **3** was inverted and its ee was enhanced from 2% to 24% (Figure S5, Supporting Information), whereas the ee of **2** (a minor product) was decreased. AC-γ-CD complex prepared by mechanical grinding gives an HH/HT ratio much higher than that obtained in aqueous solution, but the ee's of both **3** and **4** are consistently poor and the signs of chirality are the same as those obtained in solution-phase photoreaction. This suggests that the arrangement of AC pairs in the cavity of γ-CD in the solid state is greatly different from that in solution. The mesoporous silica without γ-CD modification also showed a preference for the HH dimers, probably due to the adsorption of AC in an HH fashion on the silica pore through hydrogen-bonding interactions. This observation suggests that besides the capping effect, the intrinsic characteristics of the mesoporous silica surface should also be responsible for the enhanced HH/HT ratio. However, the conversion stayed low without modification by γ-CD. The γ-CD-modified mesoporous silica obtained by the post synthesis method exhibited a much lower conversion than that obtained by the direct synthesis method, indicating that the loading amount of AC is rather low in this material. In addition, the narrower portal of γ-CD may not be fully capped in the postsynthesized material (some of the triethoxysilane substituents are not covalently linked to the pore wall), leading to a lower HH/HT ratio and the comparable ee's of **2** and **3**.

In conclusion, the photocyclodimerization of AC was well controlled by the γ-CD capped with a mesoporous silica wall, showing a switching of product selectivity and the enhancement of chemical yield of **3** and of its ee. The mesoporous silica wall-capped γ-CD not only provides a confining environment leading to higher chemo- and enantioselectivity and a diffusible network for guest substrate but also enables the recycling of the chiral source. The use of an inorganic wall to cap the portal of organic hosts provides a novel methodology for designing new supramolecular systems.

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Supporting Information Available: Synthesis of γ-CD-Si(4) and TG analysis of the extracted γ-CD-modified mesoporous silica. This material is available free of charge via the Internet at http://pubs.acs.org.

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