Chiral Imprinting

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Supramolecular Chiral Transcription and Recognition by Mesoporous Silica Prepared by Chiral Imprinting of a Helical Micelle**

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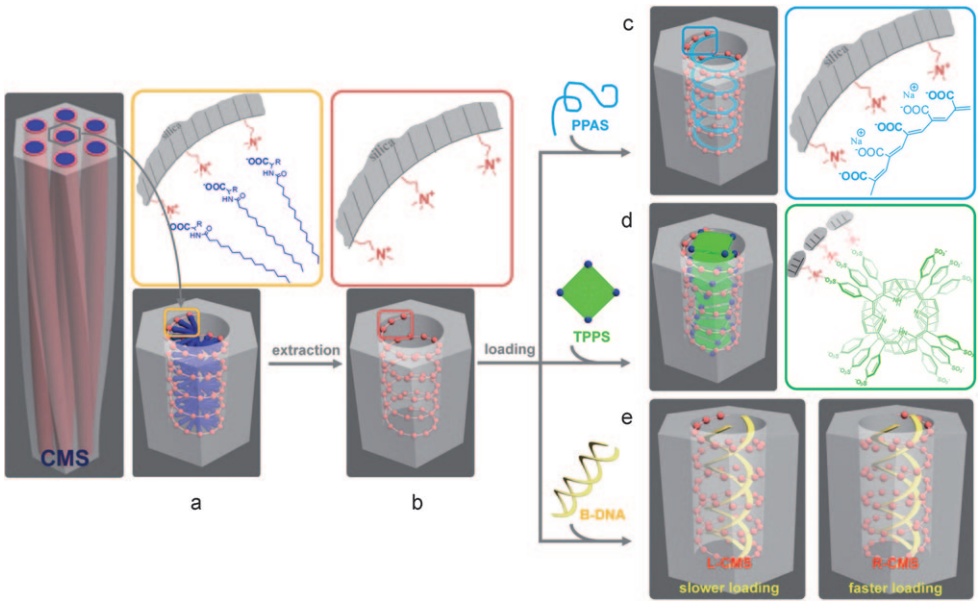
Chiral transcription and recognition play essential roles in analysis, separation, and production of chiral materials. In the past decade, chiral transcription has been utilized to generate numerous chiral supramolecular assemblies,[1–3] polymers,[4–10] and inorganic materials,[11–15] which are normally based on the organic chiral templates incorporating various chiral molecules,[7–10] macromolecules,[1–6,11] and supramolecular assemblies.[12–15] Recently, molecular chiral imprinting has become an attractive synthetic approach for the chiral recognition of small molecules.[16,17] However, there are few examples that deal with chiral imprinting on the supramolecular level, aiming supramolecular chiral transcription and recognition.



Scheme 1. a) Helical arrangement of the quaternary ammonium groups (red spheres) induced by the helical propeller-like packing of the chiral amphiphiles (blue) owing to the paired electrostatic interaction, b) the chirality imprinted in a helical arrangement of the quaternary ammonium groups remained on the mesopore surface after removal of the chiral amphiphiles by extraction, c) chiral supramolecular conformation of PPAS, d) induced chiral supramolecular stacking of TPPS, and e) chiral supramolecular (B-DNA) recognition by the chirality memorized in the helical arrangement of the quaternary ammonium groups through electrostatic pairing.

The design and synthesis of inorganic chiral materials with multifunctional properties has become a hot topic over the last few decades. Recently, we have found that the twisted secondary supramolecular structure (helix and helix assembly) of the helical propeller-like micelles of chiral anionic amphiphiles can be replicated well by the silica framework through the co-structure-directing agent (CSDA) method, yielding the highly ordered chiral mesostructured silicas (CMSs) with two-dimensional hexagonally arranged chiral channels twisting along the rod axis (Scheme 1 a).[18,19] The left-handed helical propeller-like micelles may be twisted left and give rise to the left-handed CMS (L-CMS), whereas the antipodal micelles yield the right-handed CMS (R-CMS; not shown).

As shown in Scheme 1 a, the cationic quaternary ammonium groups of the CSDA agent *N*-trimethoxysilylpropyl-*N,N,N*-trimethylammonium chloride (TMAPS) electrostatically interact with the anionic head groups of the chiral amphiphiles. Owing to the pairing effect, these functional groups may be helically aligned on the mesopore surface surrounding the helical propeller-like micelle, which is similar to the molecular imprinting process. Thus, the chirality of the primary supramolecular structure of the helical propeller-like micelles is expected to be memorized and immobilized in the helical arrangement of the functional groups on the surface of each mesopore upon removal of the template (Scheme 1 b) by extensive extraction.

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Herein, we show that such helical micelle-imprinted chirality can be delivered to the anionic linear conjugated polymer poly(propiolic acid) sodium salt (PPAS)[9] and the assembly of the disk-like molecule, tetraphenylporphine tetrasulfonic acid (TPPS), by introducing these molecules into the mesopores. Chiral conformation of PPAS and chiral column-like helical stacking of TPPS can be induced by the electrostatic pairing between the negatively charged groups ($-COO^-$ or $-SO_3^-$) and the helically arranged quaternary ammonium groups (Scheme 1c and d), which was unambiguously detected by solid-state diffuse-reflectance circular dichroism (DRCD)[20,21] in this work. Furthermore, B-DNA, which has a right-handed double-stranded helical structure, was also employed to recognize the supramolecular chirality imprinted in the CMSs.

Figure 1 shows the X-ray diffraction (XRD) patterns, N_2 adsorption–desorption isotherms, pore size distributions, scanning electron microscope (SEM) images, and high-resolution transmission electron microscope (HRTEM) images of the CMSs synthesized with *N*-palmitoyl-L-Phe and *N*-palmitoyl-D-Phe as chiral templates, and TMAPS as CDSA, at a lower temperature of 288 K.[19] As shown in the SEM images, the CMS particles have well-defined twisted rod-like morphologies with a hexagonal cross-section. All of these particles have hexagonally ordered channels twisted from two-dimensional hexagonal *p6mm*, as seen from XRD patterns and HRTEM images. An enantiomeric excess of 95% was found for both L-CMS and R-CMS by counting characteristic morphologies from 500 randomly chosen crystals in the SEM images. The chiral templates were completely removed by extensive extraction with an HCl–EtOH solution,

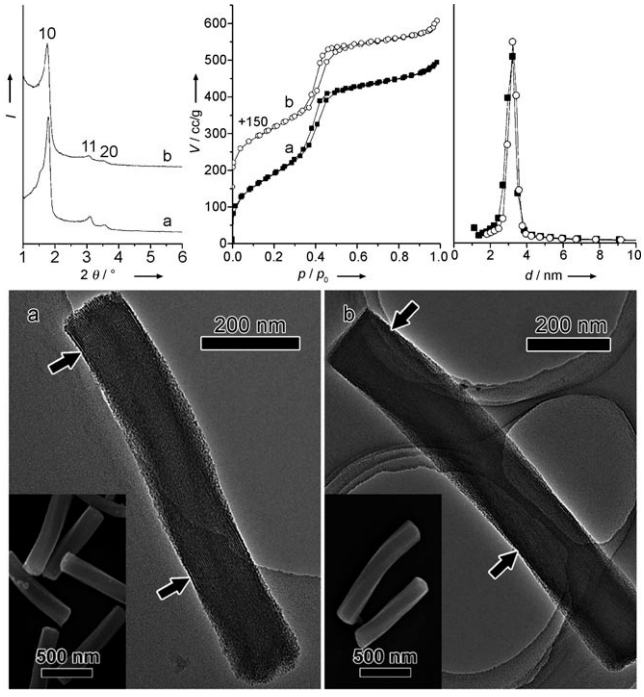

Figure 1. Upper images: XRD patterns (left), N_2 adsorption–desorption isotherms (middle), pore size distributions (right). Lower images: HRTEM and SEM (inset) images of the extracted L-CMS (a) and R-CMS (b).

and the quaternary ammonium groups rested on the silica wall, as shown by ^{13}C CP/MAS NMR spectra (see the Supporting Information, Figure S1). The extracted L-CMS and R-CMS showed very similar N_2 sorption isotherms and narrow pore size distributions, with an average value of 3.2 nm.

PPAS was obtained by polymerization of propiolic acid in a basic aqueous solution using a rhodium complex as catalyst (see the Supporting Information). The polymer that was obtained is in the *cis* form in the fresh aqueous solution, as previously reported.[9] PPAS can be readily introduced into CMS by dispersing the extracted CMS powder in the fresh aqueous solution of PPAS with vigorous stirring, probably as a result of the strong electrostatic interaction. The antipodal L- and R-CMS-PPAS complexes have mirror-image induced circular dichroism (ICD) spectra (Figure 2). The PPAS loaded

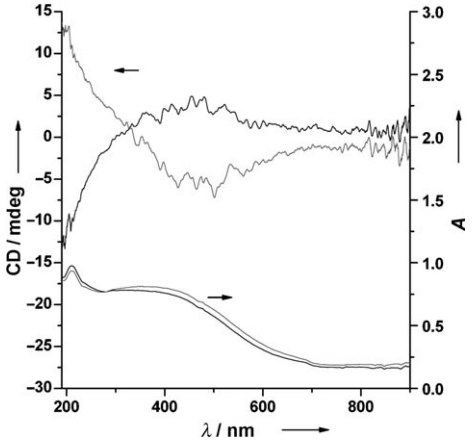

Figure 2. DRCD and UV/Vis spectra of PPAS loaded in the extracted L-CMS (black) and R-CMS (gray).

in extracted L-CMS showed ICD with a positive sign in the UV/Vis adsorption region owing to the polyacetylene main chain (about 300–600 nm) and a negative ICD around 210 nm, which is probably due to the carboxylate groups, indicating that the adsorbed PPAS was in a chiral conformation. On the other hand, the R-CMS-PPAS complex showed exactly the opposite signals in these two regions, implying that the PPAS was in an antipodal chiral conformation. Control experiments showed that no CD response was observed from the PPAS solution, extracted CMSs, *N*-palmitoyl-L(D)-Phe-PPAS mixture, and racemic CMS-PPAS complex, as well as the PPAS introduced into the calcined CMS without functional groups. The chiral supramolecular structure of PPAS is thus transcribed from the helically arranged quaternary ammonium groups immobilized on the silica wall (Scheme 1c).

The stereoregularity of the PPAS adsorbed in the extracted CMSs was studied by laser Raman spectroscopy. The peak intensity at 1324 cm^{-1} (Figure 3) is rather low, and no peak can be well resolved around 1560 cm^{-1}, implying only a small proportion of PPAS remained in the *cis* form.[9] However, the CMS-PPAS complexes have intense peaks at 1511 cm^{-1} and 1158 cm^{-1}, which can be assigned to the *trans*

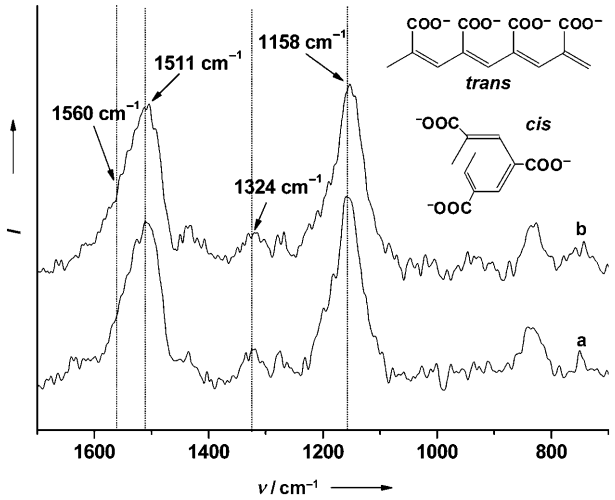

Figure 3. Laser Raman spectra of PPAS loaded in the extracted a) L-CMS and b) R-CMS. Insets are the *trans* and *cis* forms of PPAS.

form of PPAS.[9] Compared to the solution system, such *cis*–*trans* isomerization is rather fast (within 20 min, see the Experimental Section), which may be induced by the strong electrostatic interaction. The *trans* form of PPAS may provide more contacting sites with the cationic group modified mesopore surface (Scheme 1c). The linear polymer may also prefer to spread over the mesopore surface along the immobilized functional groups, rather than form helix itself.

Other anionic linear conjugated polymers with different rigidity and pendant groups, such as poly(2-carboxyphenylene-1,4-diyl) sodium salt and poly((4-carboxyphenyl)acetylene) sodium salt, were also successfully employed to transcribe the chirality imprinted on the mesopore surface (the details will be published elsewhere). Interestingly, such chiral imprinting can also induce chiral column-like helical stacking of rigid disk-like molecules.

Figure 4 shows the DRCD and UV/Vis spectra of TPPS loaded in the extracted CMSs at pH 7.0. The UV/Vis spectra of both complexes show a broad Soret band with two split

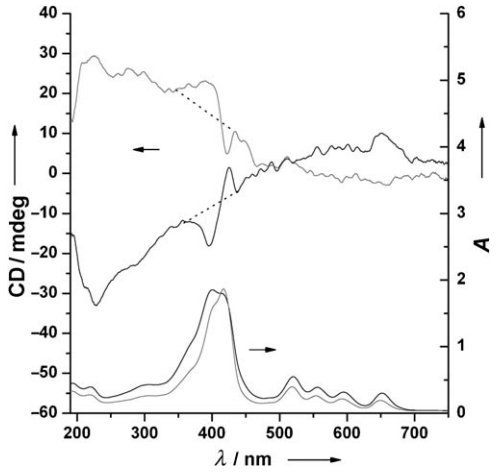

Figure 4. DRCD and UV/Vis spectra of TPPS loaded in the extracted L-CMS (black) and R-CMS (gray). A weak exciton couplet at the Soret band is denoted by the black dashed line.

peaks at 401 and 417 nm, which is in contrast with the sharp peak centered at 413 nm of TPPS in aqueous solution at pH 7.0 (Supporting Information, Figure S2). Four weak *Q* bands were well resolved in the region of 500–700 nm, which is similar to the result found in aqueous solution. However, no blue or red shift of these bands was observed to support the existence of an H or J aggregate. It strongly indicated that the TPPS disks are almost monodispersed in the mesopores with a weak coupling effect of the conjugated ring systems. Nevertheless, the antipodal L- and R-CMS-TPPS complexes showed mirror-image ICD spectra with a weak exciton couplet at the Soret band. The L-CMS-TPPS complex exhibited a positive exciton couplet, which indicates that the TPPS molecules were stacked right-handed. On the other hand, the R-CMS-TPPS complex reflected a left-handed stacking of TPPS. Interestingly, the handedness of such stacking is opposite to that of the CMSs. Two possible reasons are: 1) the handedness of the helical propeller-like micelle is opposite to that of the formed CMS crystal and the stacking of TPPS follows the handedness of the chiral imprinting; and 2) the helical propeller-like micelle gives the same handed chiral mesostructure, and the handedness of the TPPS stacking is opposite to the chiral imprinting. The latter mechanism would be more plausible, judging from the almost monodispersed weakly interacted stacking structure of TPPS in the CMS. Further studies are under progress on the detailed mechanism of such phenomena. It should be noted that the effect of linear dichroism (LD) was minimized in the present DRCD spectra by averaging the signals obtained at different angles by rotating the sample, although it is of difficulty to explain the apparently strong Cotton effect in the short wavelength region.

The CMS-TPPS complex is rather stable in most organic solvents and low-pH (<10) aqueous solutions owing to the strong electrostatic interaction. The protonation of TPPS inside the mesopores can be easily controlled by the pH of the initial loading solution. Metalized TPPS was also introduced into the CMS to induce chiral stacking. As the porphyrin rings are loosely packed and twisted to each other, such a complex is a good candidate for chiral recognition and sensing.[22–24] Additionally, the chiral imprinted CMSs would be a general guide for the chiral stacking of other functional disk-like molecules, such as C_3-symmetric polycyclic aromatic hydrocarbons,[25,26] which may lead to a broad chemical and physical applications.

B-DNA was also used to detect the imprinted chiralilty on the mesopore surface of the CMSs. The extracted L-CMS and R-CMS have the same DNA maximum loading levels (ca. 20 g mg^{-1}), as their thermodynamic stabilities in the mesopores are approximately the same (Figure 1). However, the extracted R-CMS has a faster adsorption rate than the left-handed counterpart (Supporting Information, Figure S3). Such supramolecular chiral recognition could be explained in terms of the matching between two sets of helices (Scheme 1e). The helix of the quaternary ammonium group array with an inner diameter of about 3 nm may be packed tightly with the B-DNA helix of an external diameter of about 2 nm. Despite the difference in pitch length and helical structure, B-DNA can still sense the imprinted chirality on the

mesopore surface, more easily forming a complex with the same handed helix of the functional groups. However, it should be noted that other subtle differences of the CMSs, except for the handedness, may also fluctuate the adsorption dynamics of B-DNA. It is better to prepare a pair of antipodal chiral probes (such as left- and right-handed DNA) to confirm such supramolecular chiral recognition.

In conclusion, by using chiroptical spectroscopy and molecular probes, we have clearly demonstrated for the first time that the chiral arrangement of functional groups on the mesopore surface of extracted CMS imprints the original chirality of the micelle. The novel supramolecular chiral transcription and recognition revealed in the present study not only further promote our deeper understanding of the creation of chirality in nature but also indicate the practical applications in chiral recognition and separation, asymmetric catalysis and chiral materials preparation.

Experimental Section

Synthesis of CMS samples: *N*-palmitoyl-L-Phe (or *N*-palmitoyl-D-Phe) (0.404 g, 1 mmol) and aqueous NaOH solution (0.1 mmol L^{-1}, 11.6 g) were dissolved in 20 g of deionized water with stirring at 288 K. After the compounds were dissolved, a mixture of TMAPS (Azmax, 50% in methanol, 0.258 g, 0.5 mmol) and tetraethoxylsilane (TCI, 1.2 g, 5.8 mmol) was added to the solution with stirring in 10 min. The mixture was then allowed to react at 288 K for 3 days. The products were collected by centrifugal separation and dried in the air at 313 K. The amphiphiles were removed by extraction in a 1:10 v/v HCl–EtOH solution under reflux for 24 h. The solid was separated with a centrifuge and dried in the air at 313 K to give a colorless powder.

Loading PPAS into the extracted CMS: 5 mg of PPAS was dissolved in 5 mL of ion-exchanged, degassed water with stirring in 2 min at room temperature. Then 50 mg of extracted CMS powder was dispersed in the above solution with stirring in 20 min at room temperature. The orange solid was separated with a centrifuge and dried in the air at 313 K.

Loading TPPS into the extracted CMS: 5 mg of TPPS (TCI) was dissolved in 5 mL of ion-exchanged water and a desired amount of aqueous NaOH solution (0.1 mmol/L) with stirring in 2 min at room temperature. Extracted CMS powder (50 mg) was then dispersed in the above solution with stirring in 20 min at room temperature. The orange solid was separated with a centrifuge and dried in air at 313 K.

Adsorption of DNA: Extracted CMS (100 mg) was quickly dispersed in aqueous B-DNA solution (20 g of 100 g g^{-1}, Salmon testes DNA sodium salt of approximately 2000 bp, Sigma; buffer: 0.1 mol L^{-1} NaCl, 0.01 mol L^{-1} NaH_2PO_4 and 0.01 mol L^{-1} Na_2HPO_4). The CMS suspended solution containing B-DNA was stirred at room temperature for various periods of time. Silica was settled with a centrifuge and the clear supernatant liquids were analyzed with a Lambda 20 (Perkin–Elmer, Inc.) UV/Vis spectrometer. The quantification of B-DNA dissolved in the supernatant liquid was performed by the difference of UV absorption between 260 (as the peak of UV absorption of B-DNA) and 320 nm (as background).

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