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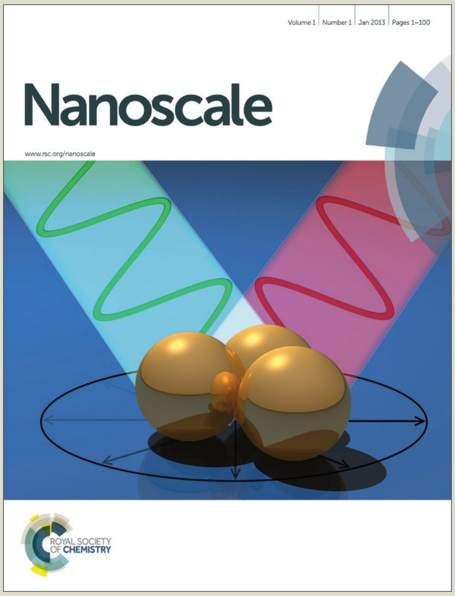

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Light and cucurbit[7]uril complexation dual-responsiveness of a cyanostilbene–based self-assembled system

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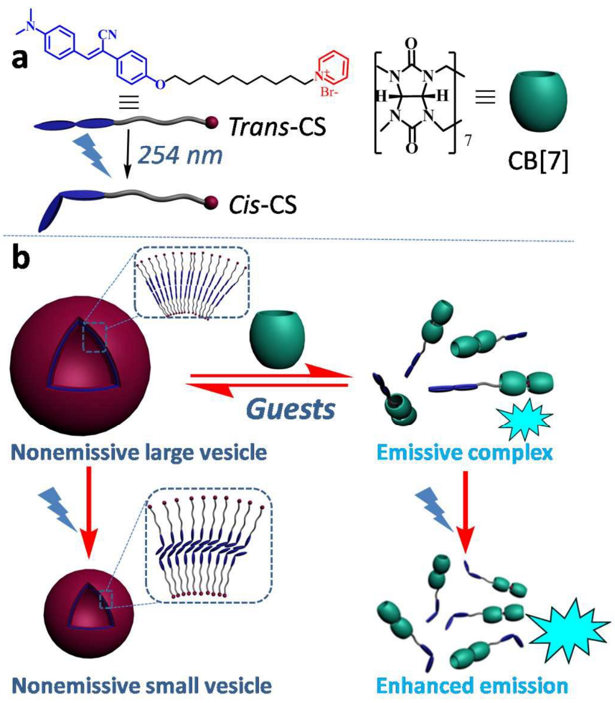
A cyanostilbene-based amphiphile (CS) was synthsized, which could self-assemble into non-emissive bilayer vesicles and ultra-thin ribbons. Cucurbit[7]uril (CB[7]) could form inclusion complex with CS with significant hypochrome effect, giving a strong blue emission from non-emissive species. CS underwent photoisomerization induced by light irradiation, which allowed the membrane contraction into smaller vesicles.

Supramolecular self-assembly produces soft materials that are dynamic, ascribed to the employed weak intermolecular interaction, such as hydrogen bonding, metal-ligand coordination and host-guest interaction.[1] On this basis, supramolecular materials possess adaptive properties, showing responsiveness to many stimuli like pH, magnetic field, temperature, light, and so forth.[2] Fabrication of light-responsive supramolecular architectures attracts more and more attention because of their application in various areas like non-invasive light-controlled drug release.[3] Many photo-switchable molecules have been developed recently. For instance, azobenzene, stilbene, spiropyran and fumaramide display *trans*/*cis* or close/open states upon light irradiation, leading to the changes of aggregates at nanoscale or even at macroscopic scale.[4] Photo-induced conformational change of the building blocks might trigger their molecular packing re-arrangement to give morphological or phase transitions, which have been regarded as an important aspect in photoresponsive materials.[3, 4]

Host molecules such as cyclodextrin, crown ether, cucurbit[n]uril and calix[n]arene show high binding constants to many photoactive molecules.[5] Attaching photo-responsiveness onto host-guest system enables the preparation of many interesting smart supramolecular materials.[6] Cyanostilbene is a novel photoactive species, the emission of which might be turned “on” from an “off” state after photoisomerization due to the suppressing twisted intramolecular charge transfer (TICT) effect.[7] For example, Zhao and coworkers utilized cyanostilbene derivatives to self-assemble into twisted fibers and uni-lamellar vesicles, which could transform into nanospheres and nanotubes with marked luminescent conversions after photoirradiation, respectively, showing potentials in bioimaging and biosensor applications.[7a-7d] In addition to the photoisomerization, utilizing host molecules with rigid cavities to control the TICT process of cyanostilbene-containing building blocks may be an alternative pathway to tune their self-assembly behavior and luminescent properties, which can provide new thoughts to fabricate novel intelligent organic optoelectronic materials.



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Scheme 1 (a) Chemical structures of CS and CB[7]. (b) Schematic representation of the controllable self-assemblies of CS by adding CB[7] and UV light irradiation.

Herein, we presented a novel cyanostilbene-based photo-responsive system. Shown in Scheme 1, CS could self-assemble into vesicles, which shall contract into smaller vesicles upon photoirradiation. CB[7] includes CS and suppress its TICT state to turn on the fluorescence of the supramolecular system with remarkable hypochromicity, emission of which can be further enhanced via photoisomerization. The great hypochromicity brought rarely reported optical variation, transforming a yellow color solution into the colorless solution.

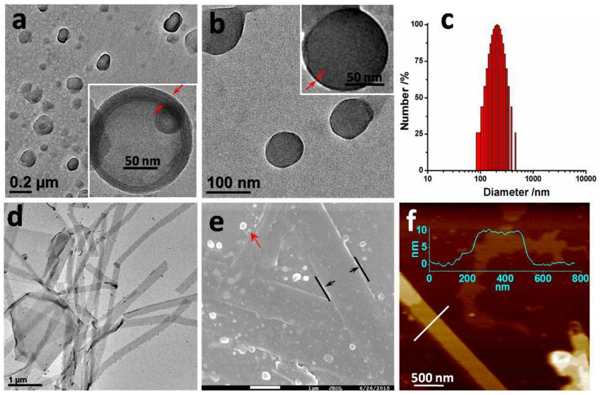

Fig. 1 Representative TEM images of multi-lamellar (a) and uni-lamellar (b) vesicles from CS assemblies (10^{-4} M), insets of which show the enlarged images of corresponding vesicles. (c) DLS size distribution of vesicular system (10^{-4} M). TEM (d), SEM (e) and AFM (f) images of nanoribbons formed at high concentration (10^{-3} M). Arrows in (e) represent the co-existence of both vesicles and nanoribbons. Inset of (f) stands for the cross-section profile of the nanoribbon.

The intrinsic amphiphilicity of CS which can be regarded as a surfactant allows its aggregation in aqueous media. At a moderate concentration (10^{-4} M), we observed the presence of nanovesicles under TEM observation (Fig. 1a-b). Unexpectedly, both multi-lamellar and uni-lamellar vesicles were present. As shown in the inset of Fig. 1a, the thickness of the multi-lamellar vesicle was about 25 nm, which embraced ca. 5 layers as counted in the magnified TEM image (Fig. S1, ESI). In contrast, the uni-lamellar vesicle only contained one layer with a mean thickness of 5 nm (Fig. 1b). According to the well established theory of vesicle formation, the value of 5 nm should be a bi-molecular length of CS with partially interdigitated hydrophobic domain, which was further verified by the molecular length of CS (ca. 2.6 nm optimized by Forcite mode of Material Studio 5.5).[8] DLS size study indicated a 100 nm to 300 nm distribution of the diameter (Fig. 1c), in agreement with the TEM observations. When the concentration of CS was further increased, the solution turned turbid, suggesting the emergence of large size aggregates. Actually, CS generated very thin ribbons at high concentration ranges (higher than $5\text{x}10^{-4}$ M), as shown in Fig. 1d. The nanoribbons, most of which showed 1 dimensional (1D) growth, also extended into some 2D membranous structures (Fig. 1d and S2). Obviously, the nanoribbons possessed great flexibility, whereby they exhibited many interlayer folding and overlapped areas (Fig. S2c) like graphene sheets. The nanoribbon formation, however, owned less fidelity, owing to the presence of vesicles along with nanoribbons, which can be considered as the orthogonal self-assemblies (Fig. 1e).[8a, 9] In order to probe the molecular arrangement of CS within the nanoribbons, AFM was employed (Fig. 1f, S3). A minimal thickness of 5 nm was obtained from the height profile (Fig. S3), in good consistent with the thickness of vesicle layers. Similarly, multiple layered nanoribbon was also present, such as the double layered nanoribbon with a 10 nm thickness displayed in Fig. 1f. This concentration-dependent topological transformation, according to our previous hierarchical self-assembly studies, is dominated by the reduction of the unfavorable edge energy of the nanoribbons by scrolling into small vesicles at low concentration ranges (vesicles have less aggregation number compared with that of nanoribbons).[8a, 10]

With the increase in concentration of CS in water (from 10^{-5} M to $3\text{x}10^{-4}$ M), the UV-vis spectra gradually red shifted from 383 nm to 395 nm, suggesting the occurrence of *J*-type π-π stacking between cyanostilbene moieties during vesicle formation (Fig. S4a). Through which we summarized the peak position against the concentration to obtain the critical aggregation concentration (GGC) of ca. $6\text{x}10^{-5}$ M (Fig. S4b). Although in our last report[7d] the aggregation-induced-emission (AIE) property of the cholesterol appended cyanostilbene was referred, this new compound barely exhibited any AIE feature (Fig. S5). The formation of aggregates was further confirmed by the decreased and red shifted absorption spectra (Fig. S6), as well as the emergence of new emission peak located at 550 nm (Fig. S7) in water as compared with that in DMSO. The negligible emission before and after self-assembly is caused partially by the presence of pyridine group which might quench the emission from aggregation via a photo-induced electron transfer (PET) process.[11] In addition, another important reason is the TICT state of *trans*-cyanostilbene, which shall generate nonradiative decay and fluorescent quenching. In order to suppress the PET/TICT process and light up this cyanostilbene vesicular system, which possesses much importance in sensor and bioimaging uses, we introduced a supramolecular strategy using host-guest interaction. When β-cyclodextrin was utilized to host CS to form the stable inclusion complex with a binding constant of 1684 M^{-1} (Fig. S8, S9), however, no significant fluorescent enhancement (only several folds resulting from the disassociation of self-quenching assembly) was observed. This is maybe caused by the relatively high polarizability (*P*) of the cavity of β-cyclodextrin (*P* = 0.20), which is intimately related to the radiative decay rate and other photophysical properties.[12] On top of that, CB[7] with a low P value (0.12) and high cavity rigidity was employed to tune the emission of the CS assemblies.

Unexpectedly, the emission color and emission intensity were significantly varied. Displayed in Fig. 2a, after the addition of CB[7], the fluorescence was turned on, of which intensity was elevated by a factor of 30 (Fig. S10). Also, the emission peak blue shifted from 500 nm to 450 nm, arousing emission color changes from yellowish green to blue. The bulky emission evolution was displayed in the inset of Fig. 2a. The CB[7]-responsive fluorescence "turn on" system was then used to fabricate white-light-emitting material. A yellow emissive luminophore (NG, in Scheme S1) was mixed with CS to form hybrids, of which luminescent emission colors transformed from yellow to white with the addition of CB[7] (Fig. S11, S12).

The absorption spectra were greatly changed (Fig. 2b). With the addition of CB[7], at first, the absorbance was slightly elevated with blue shifts, implying the disassociation of *J*-type π π-stacked arrays due to the steric hindrance from CB[7].[13] When the molar ratio of CB[7] was higher than 2 equiv., absorption peak located at 385 nm gradually decreased, whereas peak at 310 nm emerged instead. The shrunk absorption at visible region brought about great change to the bulky color of CS solution, transforming into almost colorless form form a yellow color solution (inset of Fig. 2b). Generally, the inclusion of luminophores by CB[n] produces changes to both absorption and emission spectra, and the CB[n]-induced luminescent enhancement is accounted for three factors: i) the low polarity environment of the cavity; ii) geometrical confinement which limits the rotational and vibrational freedom; iii) the suppressing of aggregation-caused-quenching (ACQ) effect.[12] In this very case, we assumed the restricted free rotation of cyanostilbene moiety should be the main reason for the fluorescent "on" and the hypochromicity. Our previous works have referred several methods to light up the emission of cyanostilbene-based supramolecular systems, which were focusing on the restriction of molecular rotation of phenylamine segment and suppressing the TICT process, such as utilizing solvent viscosity, molecular aggregation (AIE), photoisomerization, etc.[7b-d] At the same time, the remarkable hypochromicity showing in Fig. 2b is rarely reported, which might be contributed by the restriction of molecular rotation on the basis of the reports that i) CB[7] could cause large absorption blue-shift of some cyanine dyes by restricting their free rotation;[12, 14] ii) gentle hypochromicity occurred after cyanostilbene's isomerization with diminished molecular rotation.[7] In contrast, most of previous cases regarding the optical changes of dyes by CB[n] inclusion are caused by the changes in chemical equilibria, especially the protonation equilibria.[12] In ^{1}H NMR spectra (Fig. 2c, Fig. S13 in ESI), after CB[7] hosting, all alkyl protons and pyridine protons of CS shifted to up fields while the cyanostilbene shifted to down fields, indicating that CB[7]s mainly hosted alkyl chain as well as pyridine moieties (cartoons in Scheme 1). Inclusion ratio between CS and CB[7] was determined to be 1:2 according to the ^{1}H NMR and Job's plot studies (Fig. S14a, b) with an inclusion equilibrium constant of 5.6 x 10^6 M^{-2} (Fig. S14c). It should be noted that, in this inclusion complex, although cyanostilbene located at the periphery of CB[7], it still possible to restrict the molecular rotation as indicated by other CB[7]-dye studies.[12] The addition of CB[7] appended large steric hindrance to CS molecules, which hindered the ordered supramolecular arrays, leading to the disassociation of assemblies.

When competitive guests were introduced into the non-aggregated inclusion complexes, CS molecules were repelled from CB[7], of which cavities were occupied by competitive guests. It was confirmed by the recovery of both UV-vis and emission spectra (Fig. S15, S16) by adding 1-aminoadamantane hydrochloride (ADA). After that, thermostability of CS/CB[7] complexes was evaluated, elucidated by the temperature-dependent emission study (Fig. 2d). With increasing temperature, a gradual fluorescence quenching happened with red-shift from 450 nm to 460 nm, suggesting the partial disassociation of inclusion complexes at high temperature. The fluorescent intensity changes were well fitted a polynomial (inset of fig. 2d), showing potential as a favorable temperature thermometer.

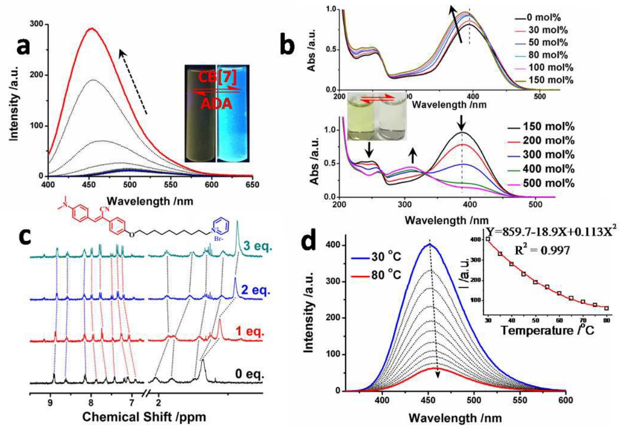

Fig. 2 (a) Emission spectra of CS (10^{-4} M) in water with the increasing molar equivalent of CB[7] (0-5 equiv.), and inset of (a) shows the bulky fluorescent changes after the addition of CB[7] and a competitive guest ADA. (b) UV-vis changes of CS (10^{-4} M) with the increasing molar equivalent of CB[7] (0-5 equiv.), and inset of (b) shows the reversible bulky color changes. (c) ^{1}H NMR titration of CS with increasing molar equivalent of CB[7]. Black, red and blue lines stand for the alkyl protons, cyanostilbene protons and pyridine protons, respectively. (d) Temperature-dependent intensity changes of CB[7]/CS complexes, interval of which was 5 ^{o}C. Inset displays the fluorescent intensity at 450 nm as a function of temperature.

Cyanostilbene moiety is capable of switching its conformation from *trans (Z)* to *cis (E)* state upon photoisomerization by 254 nm UV light.[7a-d] The isomerization of CS was confirmed by the ^{1}H NMR studies (Fig. 3a) where protons from cyanostilbene moiety shifted to up fields while other protons retained their initial locations. Via NMR integral studies, the *cis*-isomer molar ratio was higher than 75 % after 6h UV irradiation. During photo isomerization, CS in a free molecular state showed the hypochromicity (Fig. S17a) and enhanced emission (Fig. S17b), which displayed great similarity to CB[7] inclusion phenomena. This is because both CB[7] inclusion and photoisomerization would give rise to the restricted molecular rotation. According to our previous computational studies, the dihedral angle of cyanostilbene segment shall decrease from 177.7^{o} to 8.7^{o} after being transformed from *trans* to *cis*,[7b] resulting in great steric hindrance between the phenoxy and phenylamine groups (inset of Fig. 3a). For CS/CB[7] complexes in water, upon photo irradiation, absorption peak at 310 nm gradually decreased while peak at ca. 360 nm increased (Fig. 3b). Also, the absorption peak of CS aggregate blue shifted from 390 to 370 nm with diminishing intensity. Thus, we could infer that, *cis*-CS might still retain the free molecular state in the *cis*-CS/CB[7] complexes which were not disassociated by photo-isomerization. This speculation was verified by the emission (Fig. 3c) and ^{1}H NMR studies (Fig. S18). Fluorescence intensity of non-aggregated CS/CB[7] system was enhanced due to the presence of *cis*-CS, of which molecular rotation was further restricted in addition to CB[7]'s hosting. However, the *cis*-CS in aggregated state was still non-emissive (Fig.

3c), probably originated from the ACQ effect of *cis*-cyanostilbene in water.[7d]

We further investigated the morphologies of UV light-treated samples. Expectedly, no ordered aggregates were found in *cis*-CS/CB[7] complex systems ascribed to the absence of amphiphilicity. However, instead of irregular structures, nanovesicles with smaller size were present in *cis*-CS samples (Fig. 3d, S19). The mean size of the vesicles was about 50 nm, in good agreement with the DLS data (Fig. 3e). Stimulus-responsive vesicle contraction/extension, known as vesicle "breathing", has been well elucidated by Yuan's and Zhou's groups.[15] In most cases, pH-tuned de-/protonation manipulate the contraction/extension behaviors of vesicular membranes from block copolymers. Yet this photo controlled vesicle membrane contraction follows a different mechanism. As we know, the size of spherical vesicle is determined by membrane curvature that is inversely proportional to vesicle size. Therefore, the vesicle contraction actually reflects the increased membrane curvature with more compact molecular arrangement. *Cis*-isomer possesses higher rigidity and polarity than that of *trans*-CS,[7d] resulting in a tendency to lower the exposed hydrophobic domain during self-assembly process. As a consequence, the small size vesicles would be generated.

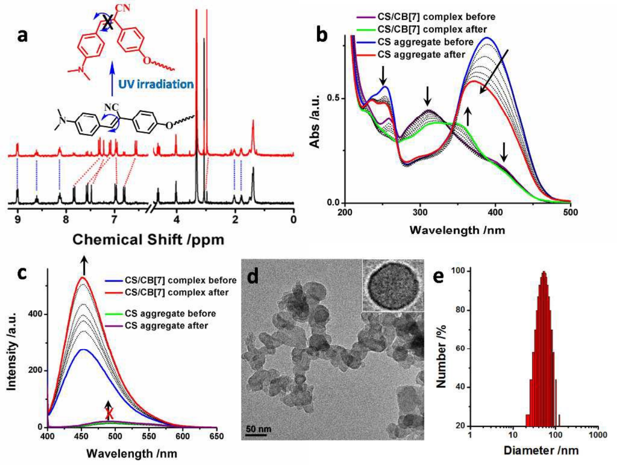

Fig. 3 (a) ^1H NMR spectra of CS before (black line) and after (red line) photo irradiation, inset of which stands for the conformational changes. UV-vis absorption (b) and emission (c) changes of CS aggregates and CS/CB[7] complexes upon photo irradiation. (d) Representative TEM image of small vesicles after UV light treatment. (e) DLS size distribution of CS aggregate after UV irradiation.

In summary, a novel cyanostilbene-based building block (CS) was designed and synthesized. CS displayed versatile self-assembly behaviors in aqueous media, generating multi-/uni-lamellar vesicles at low concentration range, while nanobelts with high aspect ratio would be formed at high concentration ranges. The addition of CB[7] shall disassociate the aggregates but greatly enhanced the fluorescence of the supramolecular system by a factor of 30 with significant hypochromicity. Upon photo-induced isomerization, the emission of CS/CB[7] complex was further enhanced without aggregation. However, the CS vesicles shrunk into smaller and non-emissive vesicles triggered by photoisomerization.

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