



Application of Macrocyclic-Based Supramolecular Assemblies Based on Aggregation-Induced Emission

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47.1 Introduction

Supramolecular chemistry has become a hot spot in contemporary chemistry research. Molecular recognition and molecular assembly are the two core contents of supramolecular chemistry [1, 2]. Macrocyclic host and guest are the major building blocks to construct supramolecular assemblies. Crown ether [3], cyclodextrin [4], calixarene [5], cucurbituril [6], and pillararenes [7, 8] are typical macrocyclic hosts and could form inclusion complexes with proper guest via non-covalent interaction such as hydrogen bonding, hydrophobic forces, electrostatic interactions, metal coordination, π - π stacking, and van der Waals forces. Therefore,

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supramolecular assemblies based on macrocyclic hosts have received wide attention from scientific researchers.

In recent years, organic molecules with aggregation-induced emission (AIE) [9] properties can effectively solve the self-quenching problem of traditional fluorescent molecules due to their unique luminescence properties and have received extensive attention from researchers. The concept of “AIE” was first reported by Tang in 2001 [10]. AIE luminophores are weakly emissive in dilute solution but significantly emissive in concentrated solution or aggregated state due to the restriction of intramolecular rotation [11]. Some typical AIE molecules include hexaphenylsilole [12], tetraphenylethene (TPE) [13], 9,10-distyrylanthracene (DSA) [14, 15], and cyanostilbene [16, 17] Schiff base derivatives [18, 19]. Therefore, considering the outstanding luminescence properties of AIE molecules, researchers have introduced macrocyclic chemistry into AIE-active systems by non-covalent interactions [20]. There are several advantages to combine macrocyclic host and AIE guest: (1) the host-guest interaction between the macrocyclic host and AIE guest restricted the intramolecular rotation of the benzene rings and enabled AIE molecules to exhibit strong fluorescence emission in dilute solution, and (2) the dynamic controllability of non-covalent interactions provides the stimuli responsiveness to the external factor, such as PH, light, competitive factor, and so on, further realizing the construction of various smart luminescent materials. In combined macrocyclic host and AIE guest, many functional luminescent supramolecular assemblies have been constructed and applied in many fields.

47.2 Application of Macrocyclic-Based Supramolecular Assemblies Based on Aggregation-Induced Emission

47.2.1 Application Based on Luminescent Materials

47.2.1.1 Artificial Light-Harvesting Luminescent Materials

As we all know, the photosynthesis plays a very important role in human life. In nature photosynthesis, light is absorbed by a large number of chlorophyll molecules, a photoinduced energy migration occurs among these chlorophyll molecules, and then the excitation energy is transferred to the reaction center, where light energy turns into chemical energy. Based on this concept, considerable efforts have been dedicated to mimic natural light-harvesting processes by realizing efficient and rapid energy transfer through a light-induced Förster resonance energy transfer (FRET) process.

Cyanostilbene derivatives are important organic fluorescent molecules in π -conjugated systems. The introduction of cyano group causes distortion of the originally planarized molecules and inhibits fluorescence quenching caused by aggregation, resulting in high solid-state luminous efficiency. In 2017, Liu and coworkers [21] reported a supramolecular artificial light-harvesting supramolecular assembly based on cyclodextrin. The supramolecular assembly was constructed from an oligo(phenylenevinylene) derivative (OPV-I), sulfato- β -cyclodextrin

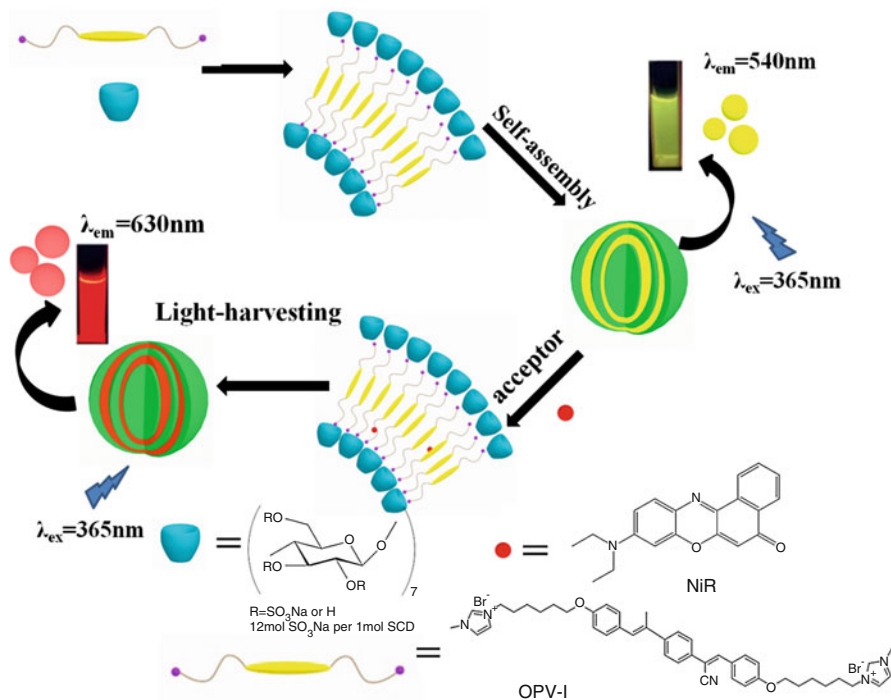


Fig. 1 Schematic illustration of the efficient artificial light-harvesting system with an oligo (phenylenevinylene) derivative (OPV-I), sulfato- β -cyclodextrin (SCD), and nile red (NiR)

(SCD), and nile red (NiR) by non-covalent interaction. OPV-I possesses good aggregation-induced emission (AIE) properties instead of fluorescence quenching in the aggregation state. Due to the host-guest interaction between SCD and OPV-I, SCD greatly lowers the critical aggregation concentration (CAC) of OPV-I, improves the AIE properties, and exhibits enhanced bright yellow fluorescence emission in dilute solution. Due to the absorption bands of NiR largely overlapped with the fluorescence band of the OPV-I/SCD, we choose NiR as acceptor. In this system, the OPV-I/SCD supramolecular assembly acted as a donor, and NiR loaded into the hydrophobic layer of OPV-I/SCD assembly acted as an acceptor. Interestingly, an efficient energy-transfer process occurred between the OPV-I/SCD assembly and the loaded NiR. Most importantly, this artificial light-harvesting system exhibited a very high antenna effect (up to 32.5) and donor/acceptor ratio (up to 125:1) that are similar to a natural light-harvesting system. This highly effective aqueous light-harvesting system is very significant for mimicking artificial photosynthesis (Fig. 1).

Based on AIE properties of cyanostilbene, Park and coworkers [22] fabricated a light-harvesting supramolecular homopolymers based on cyanostilbene derivatives and cucurbit[8]urils in aqueous solution. Four types of cyanostilbene guests (named as B, G, Y, and R) were synthesized and characterized, which showed bright blue, green, yellow, and red fluorescence, respectively. The obtained homopolymers with

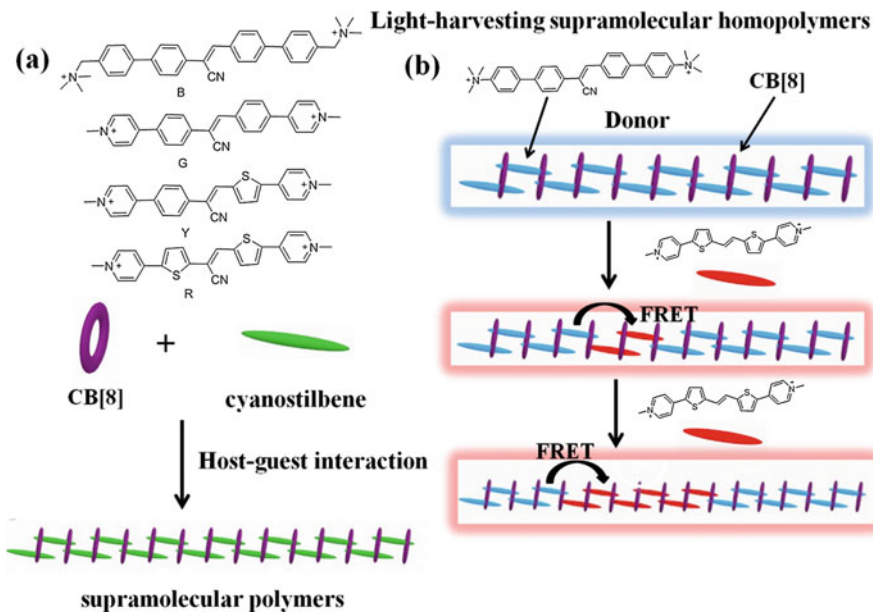


Fig. 2 Schematic illustration of the construction of cyanostilbene/CB[8] supramolecular polymer. (b) Mechanism of the light-harvesting system based on CB[8] supramolecular polymerization with B and R cyanostilbene derivatives

CB[8] and cyanostilbene derivatives through the host-guest interaction performed apparent fluorescence enhancement due to the Aggregation Induced Enhanced Emission (AIEE) effect. Among the four complexes, the fluorescence emission of B/CB[8] and the absorption of R/CB[8] have the largest spectral overlap, which could exhibit a highly efficient energy transfer with B/CB[8] as donor and R/CB[8] as acceptor. Interestingly, color-tuned supramolecular homopolymers were obtained by varying the molar ratio of B/CB[8] and R/CB[8]. Cyanostilbene/CB[8]-based fluorescent supramolecular block copolymers represented a unique and interesting artificial light-harvesting system (Fig. 2).

In another work, Wang and coworkers [23] developed two novel supramolecular artificial light-harvesting systems based on a water-soluble pillar[6]arene (WP6), a salicylaldehyde azine derivative (G), and two different fluorescence dyes, Nile red (NiR) or eosin Y (ESY). The salicylaldehyde azine derivatives possessed aggregation-induced emission (AIE) and excited-state intramolecular proton transfer (ESIPT) properties. Due to the trimethylammonium terminals of G that could form stable inclusion complex with WP6 through the host-guest interaction, it could further self-assemble to form supramolecular nanoparticles. The fluorescence emission was enhanced upon addition of WP6 due to the AIEE effect. Because of the excellent luminescence properties of WP6/G, the supramolecular assembly acted as a donor, and hydrophobic fluorescent dye NiR or ESY acted as an idea acceptor, which was successfully loaded into the hydrophobic interior of the supramolecular

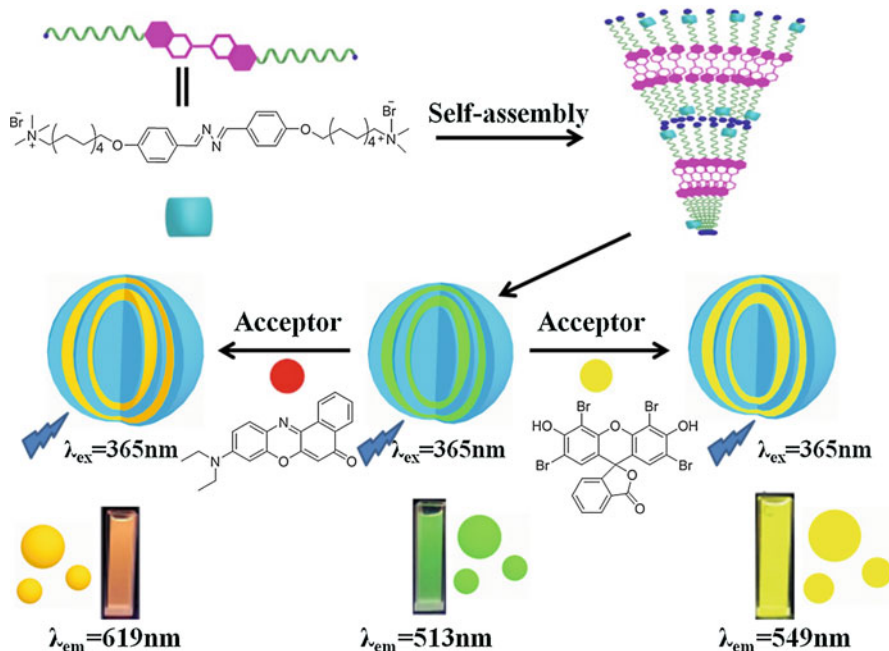


Fig. 3 Schematic illustration of the fabrication of pillar[6]arene-based light-harvesting systems in aqueous solution

nanoparticles. Significantly, efficient energy transfer process occurred between the WP6/G assembly and the loaded NiR or ESY. The energy transfer efficiency reached 55% when the mixing molar ratio of donor/acceptor was 150:1 and the antenna effect at this mixing ratio was calculated to be 25.4, which are similar to that of natural light-harvesting system (Fig. 3).

Xing and coworkers reported [24] an aqueous light-harvesting systems based on supramolecular hyperbranched polymers with naphthyl-substituted tetraphenylethylene derivative (TPE) and cucurbit[8]uril (CB[8]). The host-guest interaction between CB[8] and TPE efficiently restricted the intramolecular rotation and the non-radiative transition, thereby resulting in the strong emission in dilute solution. Moreover, highly efficient aqueous light-harvesting system was obtained with the constructed supramolecular polymers as energy donor and EY as energy acceptor.

47.2.1.2 White-Light Luminescent Materials

Organic white-light-emitting materials have received extensive attention from academia due to their potential applications in light-emitting diodes, illumination, display, and so forth. The realization of white-light emission demands either the simultaneous emission of red, green, and blue colors or at least two complementary colors. Fabricated white-light-emitting materials with supramolecular approaches such as hydrogen bonding, host-guest interaction, π - π stacking, and metal

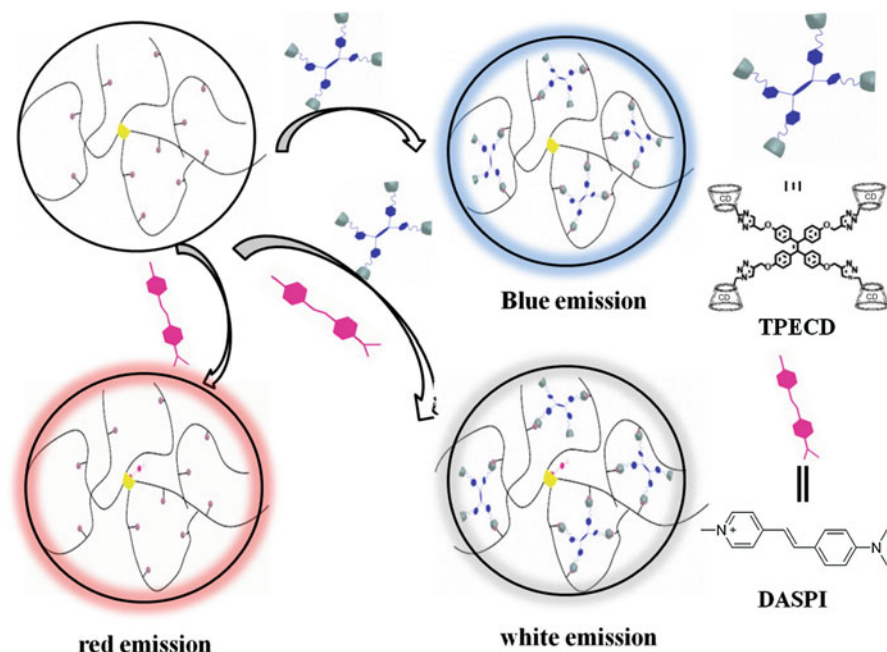


Fig. 4 The schematic illustration of tunable white-light emission highly swollen hydrogels

coordination endow the white-light emissive materials with color tunability and stimuli responsiveness.

Liu and coworkers [25] constructed tunable white-light emission highly swollen hydrogels by supramolecular self-sorting strategy. Hydrogels with good swelling properties were synthesized in situ. The hydrogel contained two binding sites, adamantly (Ad) and sulfonatocalix-[4]arene (SC[4]A) moieties. These two bonding sites could be combined with β -cyclodextrin-modified tetraphenylethene (TPECD) and 4-[4-(dimethylamino)styryl]-1-methylpyridinium iodide (DASPI). TPE is a typical AIE molecule, and DASPI is a typical twisted intramolecular charge transfer (TICT) molecule. When they encapsulated into a macrocycle cavity, the intramolecular rotation were restricted, resulting in sharply enhanced fluorescence emission. The multicolor fluorescence emissions including white light were obtained when hydrogel was swollen in aqueous solution with different ratios of TPECD and DASPI due to orthogonal supramolecular recognitions of TPECD-Ad and DASPI-SC4A pairs in hydrogel. The construction of hydrogels with adjustable fluorescence color was realized due to the self-sorting of host-guest pairs and the FRET effect between TPECD and DASPI molecules. The fabrication of multicolor fluorescent gels showed potential applications in organic luminescent displays or optical devices (Fig. 4).

47.2.1.3 Two-Dimensional Luminescent Material

In recent years, two-dimensional (2D) materials have become one of the most attractive topics in materials science. The two-dimensional supramolecular organic

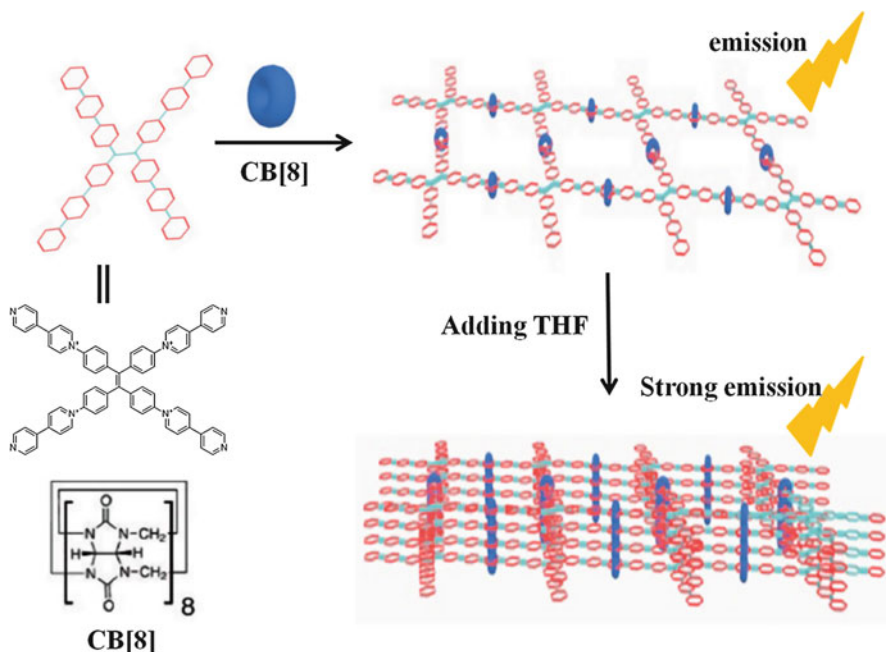


Fig. 5 The chemical structures and schematic illustration of the formation of a 2D SOF and stepwise fluorescence enhancement with the addition of THF

framework (SOF) constructed based on the host-guest interaction of CB[8] is a novel two-dimensional self-assembly strategy. This host-guest interaction maintains the planar arrangement of supramolecular assembly by the encapsulation of guest molecules in the CB[8] cavity to form two-dimensional supramolecular organic framework.

Zhao and coworkers [26] reported a two-dimensional supramolecular organic framework (2D SOF) in aqueous solution through host-guest interactions between CB[8] and four 4,4'-bipyridin-1-ium (BP) units modified TPES. CB[8] could encapsulate two BPs units into its cavity in a head-to-tail arrangement so that they were prone to aggregate to form layered structures, leading to the enhancement of fluorescence emission. Considering the formed single-layer 2D SOF, they could be further aggregated by introducing organic solvents with low and medium polarity into the solution of 2D SOF in water. The fluorescence emission demonstrated that the addition of organic solvents (THF) to the aqueous solution of SOF resulted in further enhancement of its fluorescence emission (Fig. 5).

In another work, Liu and coworkers [27] fabricated a supramolecular hydrogel by host-guest interaction with cucurbit[8]uril (CB[8]) and a tetraphenylethylene (TPE) derivative bearing four monocharged viologens (TPE-4Q). Due to rigid complexation between CB[8] and TPE-4Q, the obtained hydrogel could emit orange fluorescence. Interestingly, the obtained TPE-4Q-CB[8] hydrogel showed good responsive

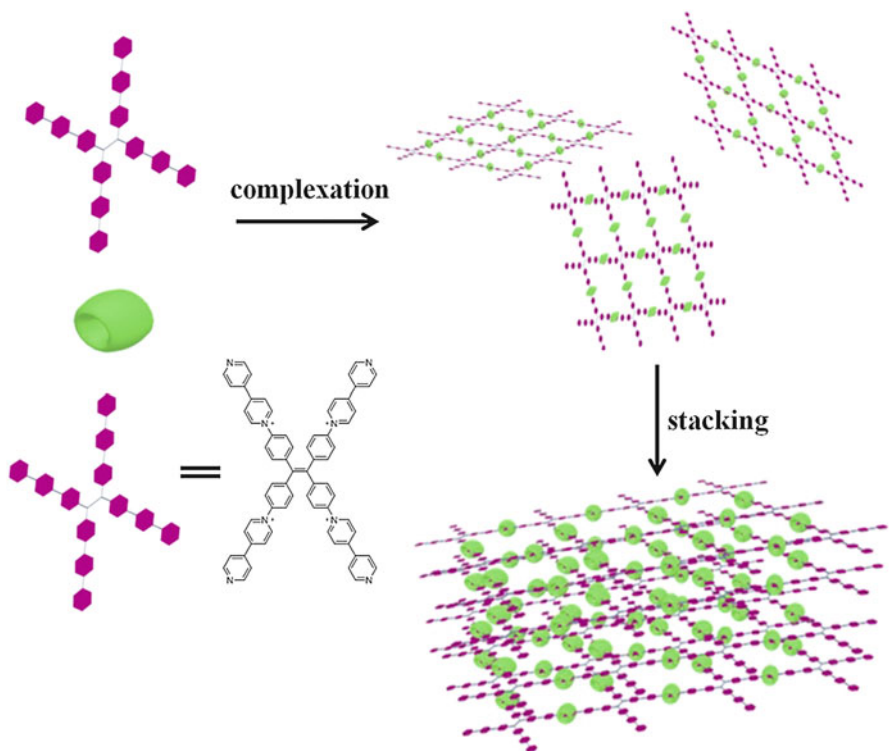


Fig. 6 Schematic illustration of the formation of TPE-4Q/CB[8] hydrogel

capability to several external stimuli, including pH, mechanical force, and competitive guests. Moreover, this two-dimensional supramolecular hydrogel could specifically adsorb π -conjugated anionic dyes in water with high adsorption efficiency through the π -stacking interaction and the electrostatic interaction (Fig. 6).

Cao and coworkers [28] reported shape-controllable and fluorescent supramolecular organic frameworks through host-guest complexation of CB[8] with tetra (1-carboxyethyl-pyridinium) tetraphenylethylene derivatives. CB[8] encapsulated two pyridinium(vinyl) arms of neighboring molecules with a head-to-tail stacking pattern, which could lead to planar or curved supramolecular network-type layers. Layers 3 or 4 could be further stacked or aggregated into supramolecular cuboids and spheroids. These two-dimensional supramolecular organic frameworks exhibited interesting photophysical properties. Compound 1 underwent a large red shift of 82 nm with the addition of CB[8], while compound 2 underwent fluorescence quenching. When adamantane derivative having a stronger binding ability to CB[8] was added to the compound 2 assembly, compound 2 could be competed from the cavity of CB[8], and fluorescence was recovered. This stimuli-responsive behavior was applied in adamantane-regulated cell imaging in HeLa cells (Fig. 7).

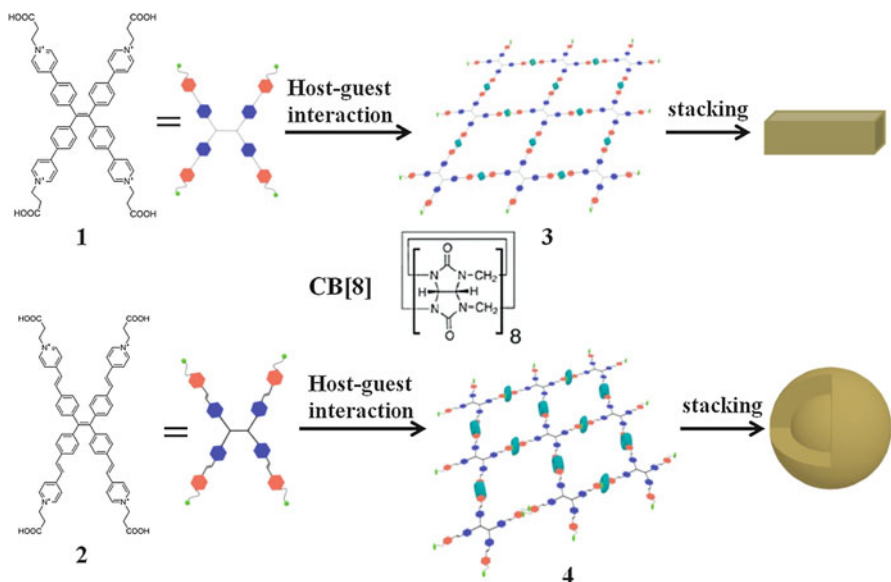


Fig. 7 The chemical structures of 1, 2, and CB[8] and schematic illustration of shape-controllable and fluorescent supramolecular network-type layers (3 and 4) by host-guest complexation. Layers 3 or 4 could be further stacked or aggregated into supramolecular cuboids and spheroids

47.2.2 Application Based on Stimuli-Responsive Materials

Construction of stimuli-responsive materials by supramolecular strategy has attracted increasing interests of researchers due to their various applications in drug delivery, cell imaging, and smart functional materials, controlled by various external stimuli, such as pH, temperature, enzymes, light, and so on. AIE luminophores were introduced into these stimuli-responsive systems for their high sensitivity and fast response via the change of fluorescence.

47.2.2.1 pH-responsive Materials

Tian and coworkers [29] fabricated a pH-responsive supramolecular polymer based on a bis-p-sulfonatocalixarene host and a tetraphenylethylene derivative guest by the unique host-guest interaction of calixarene-induced aggregation (CIA). The protonated pyridinyl guest could be included into the cavity of bis-p-sulfonatocalixarene via electrostatic interaction, leading to the formation of supramolecular polymer and the enhancement of yellow fluorescence emission, and the AIE signals turned *ON*. The addition of base resulted in the deprotonation of pyridinyl guest, which caused the disassembly of the supramolecular polymer. Interestingly, the AIE signals exhibited two states in different solvents. The deprotonation of guest could aggregate in water due to the hydrophobic properties, leading to the switching fluorescence color from yellow to green. In a mixed solvent of H₂O and THF (v:v = 1:1), the AIE signals turned *OFF*

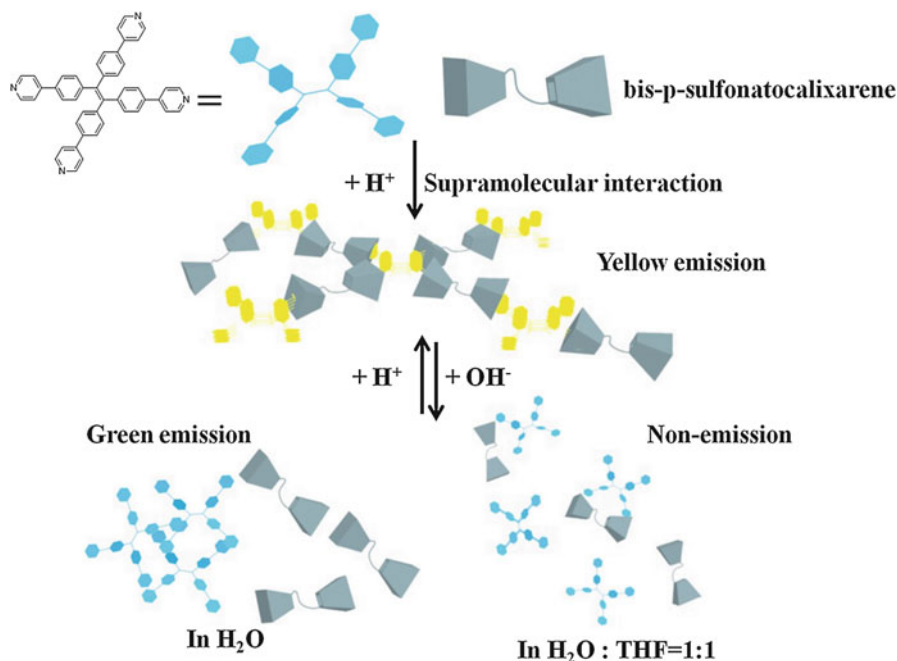


Fig. 8 Schematic illustration of the fabrication of pH-responsive supramolecular polymer based on a bis-p-sulfonatocalixarene host and a tetraphenylethylene derivative guest

due to the outstanding solubility. This pH-responsive supramolecular polymer provided a new platform to fabricate smart supramolecular polymeric materials (Fig. 8).

Sessler and coworkers [30] constructed a pH-responsive bola-type supra-amphiphile from a water-soluble calix[4]pyrrole (WC4P) and a tetraphenylethylene containing pyridine bis-*N*-oxide. The bola-type supra-amphiphile exhibited strong fluorescence emission due to the aggregation induced by host-guest interaction. As we all know, neutral carboxylic acid groups and anionic carboxylate groups could be interconverted reversibly by adjusting the pH. Under neutral or basic conditions, the supramolecular complex further self-assembled to form vesicles. By adding HCl to decrease the pH from 7.4 to 4.0, the vesicles were disassembled to release the guest due to the protonated carboxylic acid. When the pH was adjusted back to 7.4, the vesicles were formed again. The construction of a pH-responsive supramolecular assembly provided a new platform for the controlled release of drugs (Fig. 9).

Huang and coworkers [31] reported supramolecular nanoparticles with near-infrared emission enhanced by pillararene-based molecular recognition in aqueous solution. The unique NIR AIE-active supramolecular nanoparticles were constructed with WP5 and cyanostilbene derivative (5) by host-guest interaction in water. Cyanostilbene derivative (5) self-assembled into nanoribbons with relatively weak emission in low concentration via π - π stacking interactions. Significantly, when water-soluble pillar[5]arene (WP5) was added into the nanoribbons (5), the topology morphology transformed into

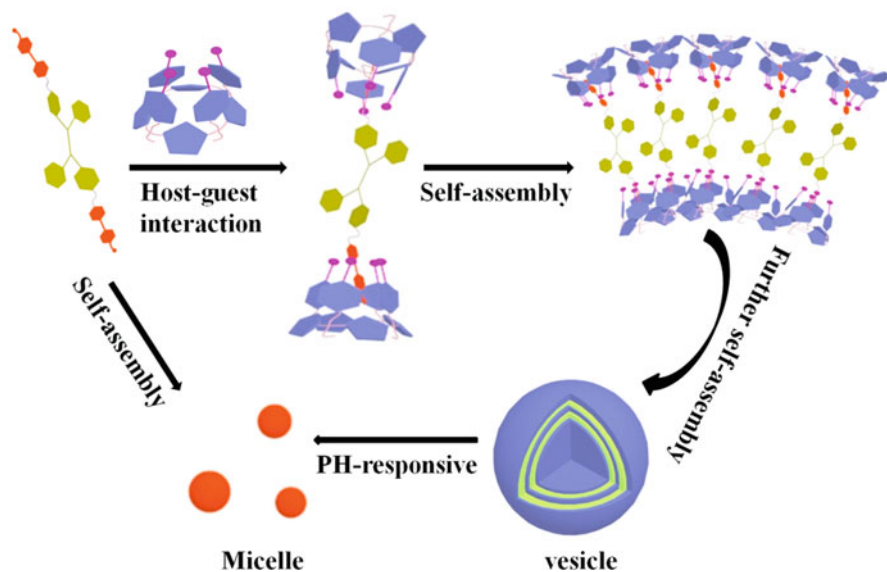


Fig. 9 Schematic illustration of the construction of bola-type supramolecular vesicles through host-guest interaction with calix[4]pyrrole and its pH-triggered vesicle-to-micelle transition

nanoparticles accompanied with stronger NIR fluorescence emission due to the host-guest complexation enhanced aggregation between WP5 and the trimethylammonium groups of the cyanostilbene derivative. Interestingly, the supramolecular nanoparticles exhibited pH responsiveness. The carboxylate groups of WP5 converted to WP5H after the addition of acid, meanwhile the nitrogen atom of (5) on the diethylamine group could also be easily protonated by acid which resulted in the disassembly of WP5/5 complexation. This type of NIR-emissive water-soluble supramolecular nanoparticles exhibited a considerable potential in cell imaging (Fig. 10).

47.2.2.2 Light-Responsive Materials

In 2014, Liu and coworkers [32] proposed a new concept as calixarene-induced aggregation (CIA): complexation with p-sulfonatocalix[n]arenes (SCnAs, $n = 4-8$) promoted the aggregation of aromatic or amphiphilic molecules by lowering the critical aggregation concentration (CAC), enhanced the aggregate stability, and regulated the degree of order in the aggregates. The self-assembled fluorescent nanoparticles were prepared in water by means of calixarene-induced aggregation of a tetraphenylethene derivative (QA-TPE) mediated by p-sulfonatocalix[4]arenes. Free QA-TPE was weakly emissive under lower concentration owing to its weak aggregation ability. When p-sulfonatocalix[4]arenes were added to the QA-TPE solution, the fluorescence emission was enhanced and was clearly observed by naked eye due to calixarene-induced aggregation (CIA). Because of the photocyclization of QA-TPE upon irradiation by UV light, the free QA-TPE unit was cyclized to convert into diphenylphenanthrene (QA-DPP), which resulted in aggregation-induced

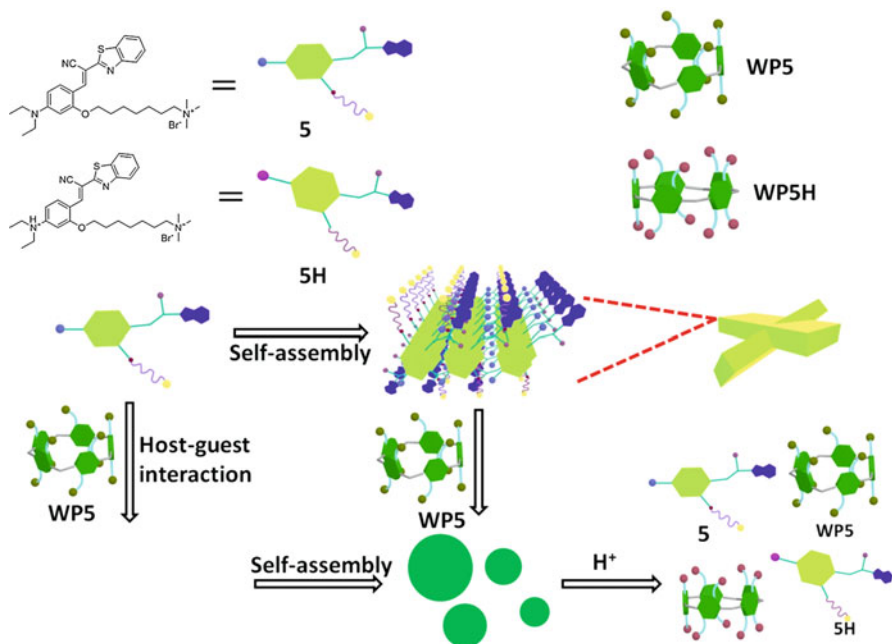


Fig. 10 Schematic illustration of NIR AIE-active supramolecular nanoparticles by pillararene-based molecular recognition in aqueous solution and pH responsiveness of supramolecular nanoparticles

quenching (ACQ) phenomenon. Free QA-TPE showed strong fluorescence in a dispersed state; in contrast, the supramolecular nanoparticles showed non-emissive under UV light irradiation due to the ACQ. Photoswitching the fluorescence of free QA-TPE and the self-assembled nanoparticles was achieved due to the photoreactivity of QA-TPE. The stimuli responsiveness of the AIE-active supramolecular nanoparticles was highly desirable for constructed functional luminescent materials (Fig. 11).

Zhu and coworkers [33] reported dual-responsive aggregation-induced emission active supramolecular nanoparticles for gene delivery and bioimaging. This dynamic supramolecular functional nanomaterials assembled from the *N,N*-dimethylethylenediamine-functionalized β -cyclodextrin (DMAE-CD) host and the adamantane-modified dimethylaminoazobenzene (DMA-Azo-AD) guest via host-guest interaction. The hydrophobic DMA-Azo-AD has the property of aggregation-induced emission; this unique AIE behavior provided a platform for bioimaging. In addition, DMA-Azo-AD could be protonated under acidic conditions, resulting in a prominent hydrophobic to hydrophilic transition and the disassembly of supramolecular nanoparticles. Meanwhile, the same phenomenon was emerged when the nanoparticles were exposed to visible light (450 nm), because of the photoisomerization of trans-cis conversion of DMA-Azo-AD. The hydrophilic cationic β -CD derivative afforded an effective plasmid DNA (pDNA) condensation ability. Significantly, the resulting

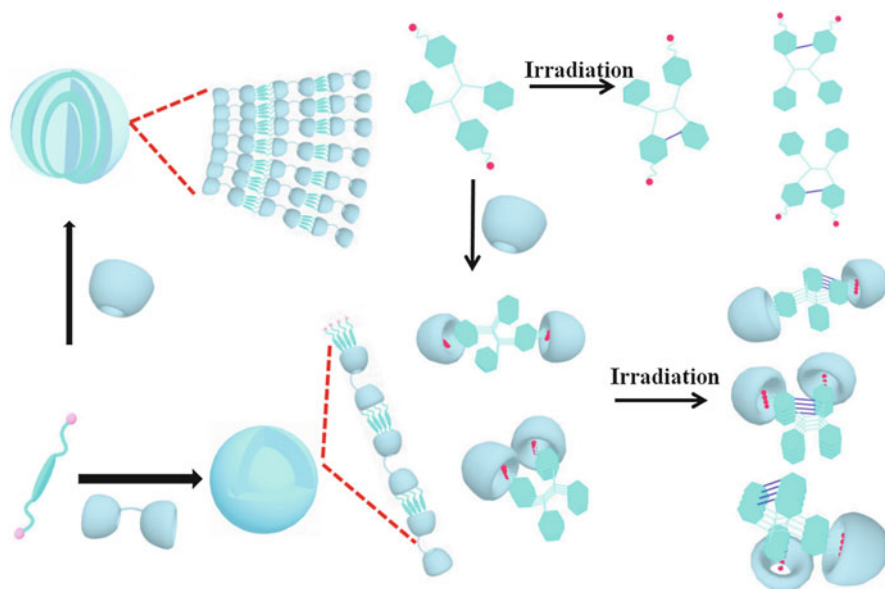


Fig. 11 (a) The mechanism of calixarene-induced aggregation with a tetraphenylethene derivative (QA-TPE) and p-sulfonatocalix[4]arenes. (b) Schematic illustration of the photocyclizations with free QA-TPE and the SC4A/QA-TPE assembly

supramolecular nanoparticles (SNPs) exhibited a morphological transition in response to both pH and visible light, making them promising candidates for controlled therapeutic agent delivery (Fig. 12).

Ma and coworkers reported [34] photo-controlled fluorescence on/off switching of a pseudo[3]rotaxane, which was fabricated based on the non-covalent host-guest interaction between a diarylethene derivative G and a pillar[5]arene derivative H. When one G molecule encapsulated into the cavity of two H molecules, significant fluorescence enhancement could be observed due to the restricted intramolecular rotation of TPE. On account of the reversible photoisomerization properties of the diarylethene moieties between the open and closed forms, the fluorescence emission of the TPE moieties of the assembly could switch “on” and “off” reversibly by alternating the visible and UV light irradiation. As a result, the present supramolecular switch provided a promising application in storage media, reversible erase/rewrite systems, and photo-controlled molecular device (Fig. 13).

47.2.2.3 Other Stimuli-Responsive Materials

Guo and coworkers [35] further researched the calixarene-induced aggregation (CIA) behavior. Tetraphenylethene derivatives (TQA-TPE) were employed as model substrates due to their properties of aggregation-induced emission (AIE) by using three typical macrocyclic hosts, cyclodextrins, cucurbiturils, and p-sulfonatocalixarenes, to study the complexation-induced aggregation behaviors.

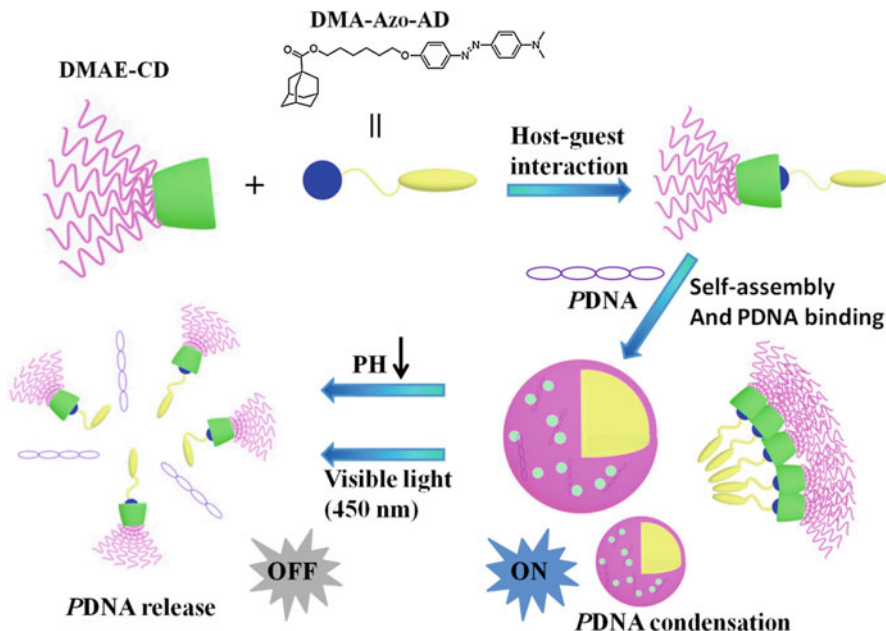


Fig. 12 Schematic illustration of AIE-active supramolecular nanoparticles formed by the self-assembly of a supramolecular amphiphile via host-guest interaction and its pH or visible light-triggered pDNA release as well as cell imaging

Upon the addition of calixarene to TQA-TPE solution, highly ordered aggregates were formed. When adding excess calixarene, the formed aggregates disassembled and the simple complex formed. The obtained results exhibited that both host-guest interactions and electrostatic interactions of p-sulfonatocalixarenes play an important role in the complexation-induced aggregation.

Yang and coworkers [36] fabricated a supramolecular complexation with mono-sulfonicpillar[5]arene (MSP5) and a neutral guest with tetraphenylethene (TPE-(Br)₄) by host-guest interactions. TPE-(Br)₄ was encapsulated into the cavity of MSP5, restricting the intramolecular rotation of TPE, which resulted in the enhanced fluorescence emission. Due to the sulfonic group of MSP5 having a strong binding affinity toward alcohols via hydrogen bonds, the supramolecular complex was destroyed, and the fluorescence was decreased after the addition of butanediol. Furthermore, temperature and competitive guest also resulted in the destruction of supramolecular complex. Therefore, the multi-responsive properties provided promising application as a chemical sensor toward alcohol analogs, ethylenediamine, and temperature (Fig. 14).

47.2.3 Application Based on Biology Materials

Some macrocyclic molecules, such as cyclodextrin and cucurbituril, exhibit good water solubility, low toxicity, biocompatibility, and biodegradability. Therefore,

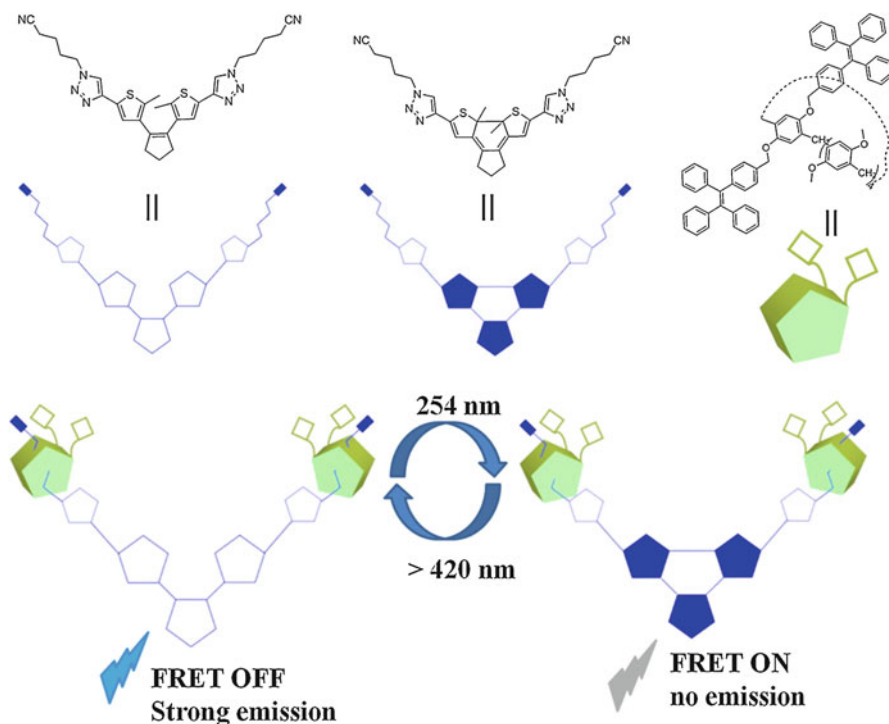


Fig. 13 Schematic illustration of photo-controlled fluorescence on/off switching of a pseudo[3]rotaxane

supramolecular assemblies based on AIE molecules and these macrocyclic molecules have attracted increasing interests for bioimaging and drug delivery in recent years.

47.2.3.1 Loading Drugs

Liu and coworkers [37] constructed supramolecular drug delivery systems via tetraphenylethene (TPE)-bridged β -CD tetramers (TPECD) with the adamantly grated hyaluronic acid (HAAD). Utilizing strong host-guest interactions between cyclodextrin and adamantane, HACD could be effectively non-covalently cross-linked together to form a compact assembly and enhanced the fluorescence of supramolecular assembly due to the AIE properties of TPE. The hydrophobic environment of TPE provides a drug-loaded hydrophobic environment, and HA provided good targeting of cancer cells. Therefore, the constructed supramolecular nanoassembly could effectively deliver the anticancer drug DOX to cancer cells, release the drug in the acidic environment of cancer cells, and enhance the lethality against cancer cells (Fig. 15).

Chen and coworkers [38] reported supramolecular nanomedicine based on amphiphilic brush copolymer for cancer therapy. The amphiphilic supramolecular brush copolymer CB[8]/(PEG-Np•PTPE) was constructed on the basis of a novel host-

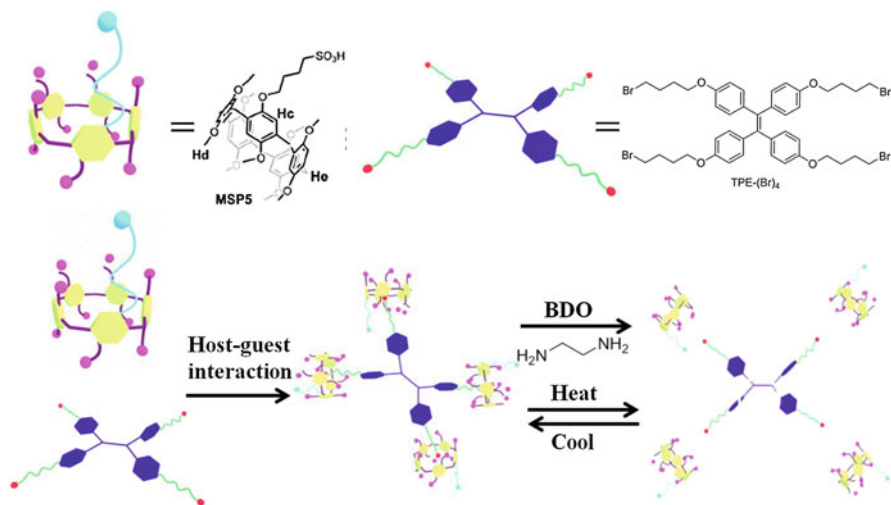


Fig. 14 Schematic illustration of the multi-responsive supramolecular complexation with monosulfonicpillar[5]arene (MSP5) and tetraphenylethene (TPE-(Br)₄) by host-guest interaction

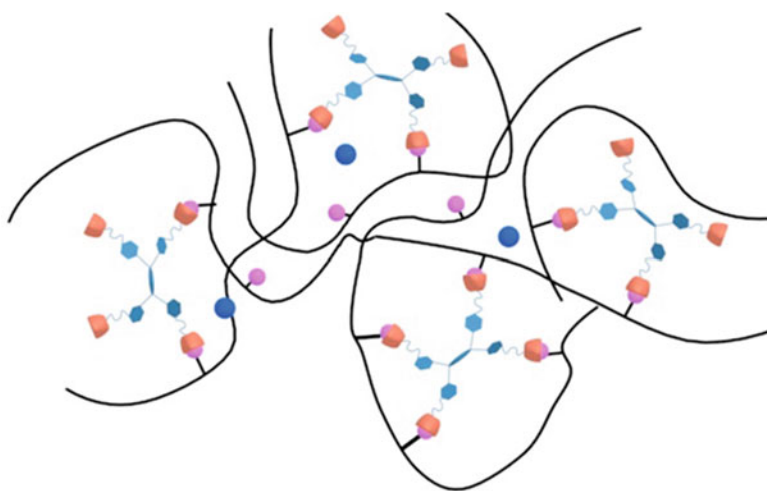


Fig. 15 Schematic illustration of the fabrication of supramolecular drug delivery systems

guest interaction between cucurbit[8]uril (CB[8]), 4,4'-bipyridinium derivative, and PEGylated naphthol (PEG-Np) and self-assembled into supramolecular nanoparticles (SNPs) in water. Furthermore, DOX was loaded into the hydrophobic core of SNPs. Tetraphenylethene (TPE) group acts as a donor, and the drug DOX acts as an acceptor, which resulted in a Förster resonance energy transfer (FRET). In the aggregation state, the fluorescence was quenched by the FRET and ACQ effects. When the DOX-loaded SNPs entered the cancer cell, the loaded drug was released due to intracellular reducing

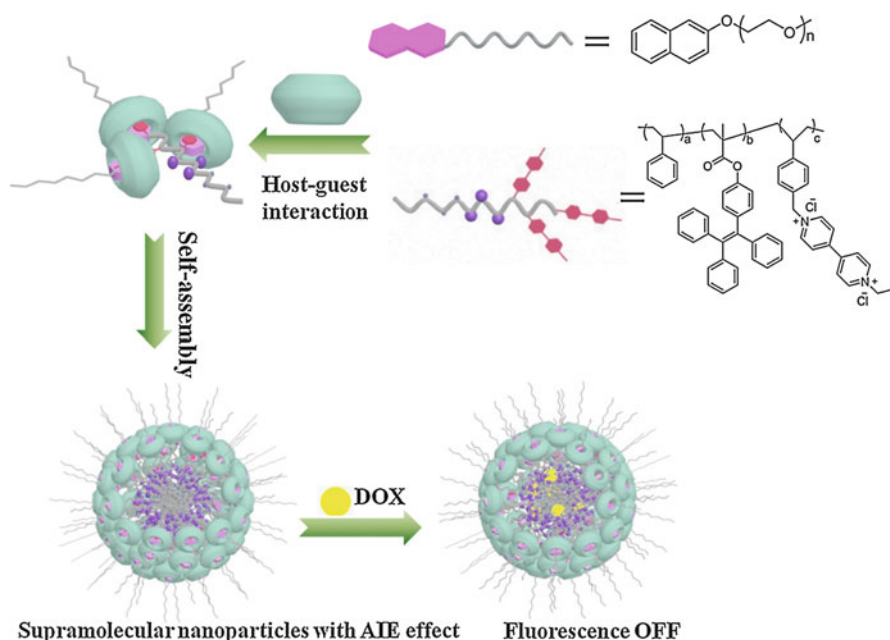


Fig. 16 Schematic illustration of the supramolecular nanomedicine based on amphiphilic brush copolymer for cancer therapy

agents and low pH environment, and then the fluorescence was recovered. These multifunctional supramolecular nanomedicines possessed self-imaging and controllable drug release ability and exhibited great potential in cancer therapy (Fig. 16).

47.2.3.2 Cell Imaging

In 2014, CD-modified TPE luminogens based on intramolecular host-guest inclusion were reported by Tang and coworkers [39]. TPEs functionalized with α -, β -, or γ -CD were synthesized by esterification reaction of CD with monocarboxylic acid-substituted TPE. Both TPE- α -CD and TPE- β -CD exhibited strongly enhanced fluorescence, attributing to the phenyl rings of TPE threaded into the cavity of CD, which restricted the rotation of phenyl rings. However, TPE- γ -CD showed a weaker fluorescence due to the larger-sized cavity. The TPE-CDs were biocompatible and could be utilized to image the cytoplasm of living cells. In another work, Yu and coworkers [40] constructed a host-guest complex based on a monofunctionalized pillar[5]arene and a tetraphenylethene derivative. The host-guest interactions restricted the intramolecular motion of the aromatic rings, resulting in an enhanced fluorescence emission. These results demonstrated that aggregation-induced emission system based on host-guest interaction showed enormous potential applications in cell imaging.

Huang and coworkers [41] reported a supramolecular 1D nanorod in water with two four-armed TPE-based derivatives containing electron-rich naphthalene (TPE-NP) and electron-deficient paraquat (TPE-PQ) groups driven by CT interactions, which

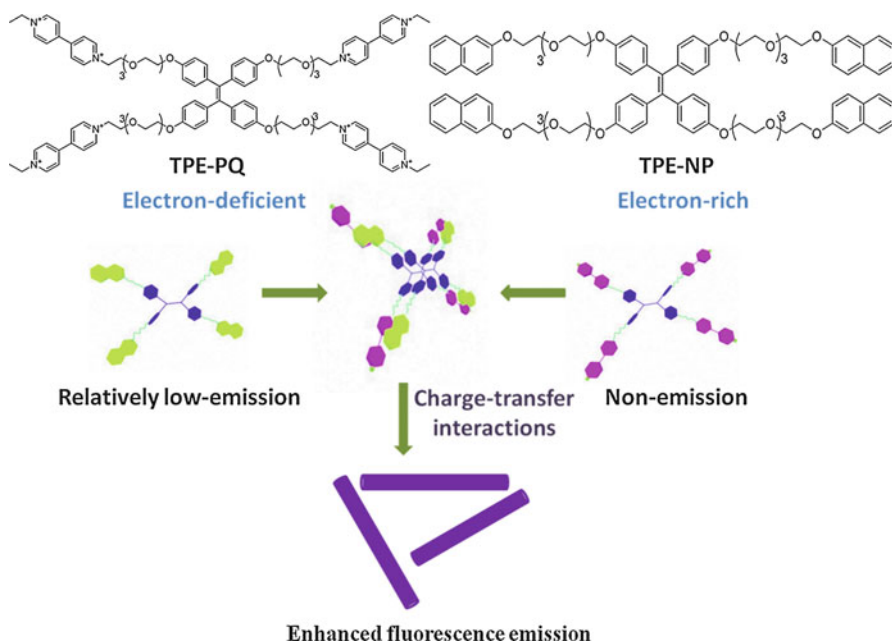


Fig. 17 Schematic illustration of the fabrication of supramolecular nanorod with TPE-PQ and TPE-NP

restricted the intramolecular rotation of benzene rings to enhance the emission obviously. Due to the TPE-PQ exhibiting high toxicity for the cells, a difunctional negatively charged water-soluble pillar[6]arene (H) was used to reduce the toxicity of TPE-PQ by forming a supramolecular complex H/TPE-PQ with TPE-NP. The carboxylate groups on H were protonated into carboxylic acid groups with addition of HCl, resulting in the disassociation of the complex. Meanwhile, the assembly and disassembly behavior of H/TPE-PQ complex was accompanied by the changes of fluorescence. Based on the above mentioned, the ternary supramolecular system containing H, TPE-NP, and TPE-PQ could be utilized as a living cell imaging agent. Because the pH value in cancer cells was lower than that in normal cells, TPE-PQ disassociated from the cavity of H in cancer cells and interacted with TPE-NP to form a stable CT complex, resulting in enhanced fluorescence emission in the cytoplasm (Fig. 17).

47.2.4 Application Based on Sensor Materials

47.2.4.1 Metal Ion

Liu and coworkers [42] reported a highly sensitive and selective fluorescence off-on K^+ probe based on host-guest molecular recognition. In this work, crown ether-modified tetraphenylethene (TPE) derivative was synthesized. The TPE core served as AIE-active luminophore, and benzo-15-crown-5 served as K^+ -recognizing moieties. With the addition of K^+ , tetraphenylethene was aggregated which turned on the

fluorescence emission, therefore the detection of K^+ was achieved. Based on the abovementioned method, a pH-responsive supramolecular polymer for Pd^{2+} detection was fabricated by Yin and coworkers [43]. Supramolecular polymer was formed by host-guest interactions with dibenzo[24]crown-8-modified tetraphenylethene moieties as the chromophore and a bisammonium salt with two dibenzylammonium (DBA) units as the responsive site. It exhibited much higher fluorescence emissions than its monomer due to the AIE properties of TPE. Interestingly, the fluorescence intensity of supramolecular polymer was decreased dramatically by the addition of Pd^{2+} ions. Therefore it could be used in the detection of Pd^{2+} ions (Fig. 18).

Yang and coworkers [44] reported a luminescent cross-linked macrocycle polymer (CMP) as a two-photon fluorescence sensor for Fe^{3+} and organic molecules, which was synthesized by Sonogashira-Hagihara cross-coupling with pillar[5]arene and TPE. Significantly, the combination of TPE with pillar[5]arene gives the polymer many excellent properties, including two-photon luminescence properties and porous structure. In order to investigate the significant impact of pillar[5]arene, cross-linked conjugated microporous polymer without pillararene rings didn't show any similar two-photon fluorescence phenomenon, and the fluorescence emission was decreased and blue shifted. The resulting luminescent CMP material exhibited high sensitivity toward Fe^{3+} . It was clearly observed that only Fe^{3+} exhibited a remarkable fluorescence quenching, which might be attributed to the size-matching effect of pillar[5]arene toward Fe^{3+} . Meanwhile, its fluorescence could also be quenched by 4-aminoazobenzene. These experimental results demonstrated that pillar[5]arene-TPE-CMP could also be a potential fluorescent sensor for detection of ions/organics (Fig. 19).

47.2.4.2 Organic Molecules

Huang and coworkers [45] constructed an AIEE fluorescent supramolecular cross-linked polymer network based on TPE-containing conjugated polymer with pillar[5]arene units (P5-TPE) and a symmetric BB type cross-linker (G) through host-guest interactions. The host-guest complex inhibited the intramolecular rotation of TPE moieties and further promoted aggregation-induced emission enhancement (AIEE). Interestingly, the fluorescence intensity of the supramolecular polymer network decreased dramatically upon addition of TNP. The conjugated supramolecular polymer provided a promising application in detection of explosive compounds in waste water (Fig. 20).

47.3 Conclusion

Overall, this chapter has summarized the application of macrocycle-based aggregation-induced emission (AIE) supramolecular assemblies. Macrocyclic host compounds, such as crown ether, cyclodextrin, calixarene, cucurbituril, and pillararene, have been utilized to fabricate AIE-active luminescence supramolecular assemblies by non-covalent interactions. Combining the macrocycle host and AIE guests endows the supramolecular assemblies various excellent characteristics, including outstanding luminescence behavior and dynamic controllability. First, taking advantage of its

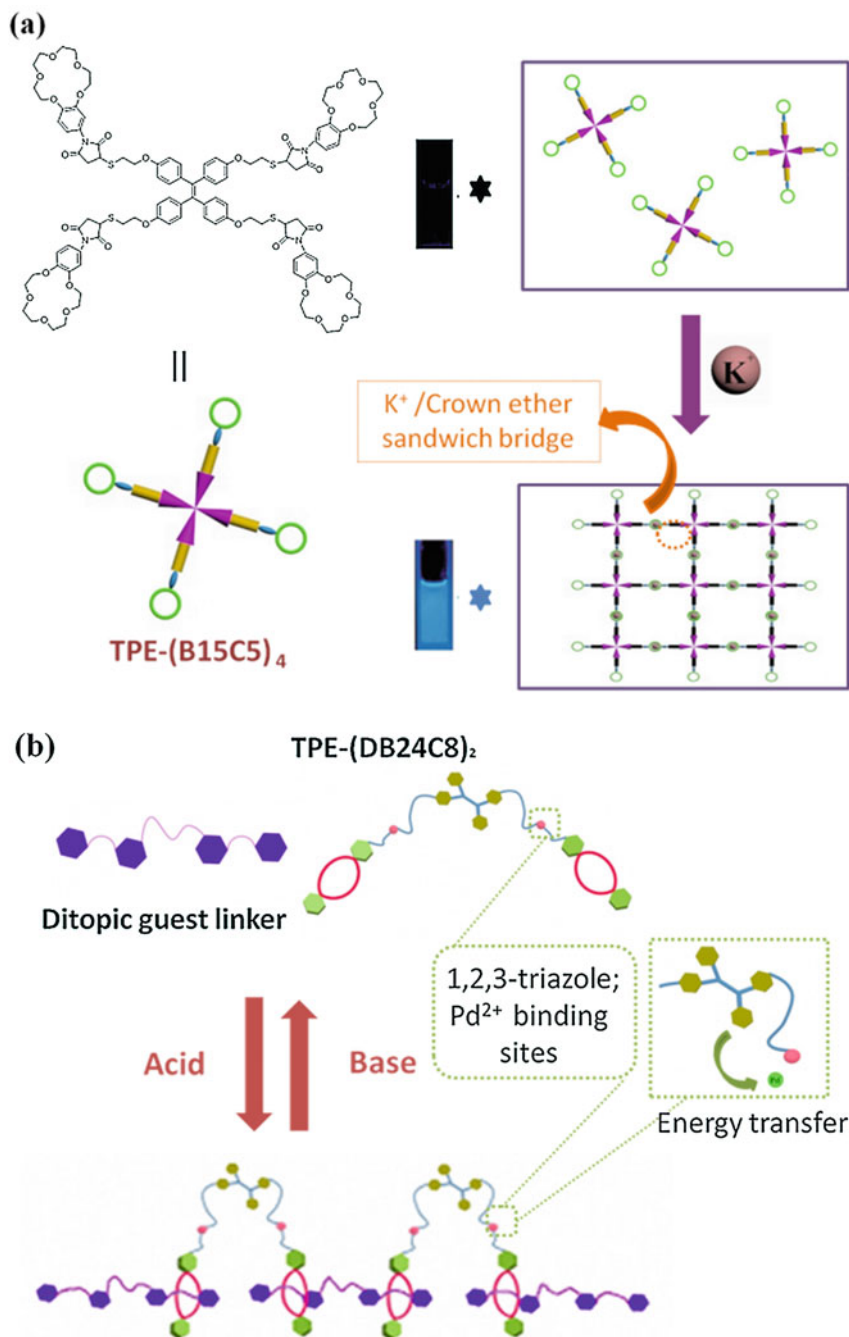


Fig. 18 (a) Schematic illustration of a highly sensitive and selective fluorescence off-on probe based on host-guest molecular recognition with crown ether-functionalized tetraphenylethene. (b) Schematic illustration of pH-responsive supramolecular polymer for Pd²⁺ detection

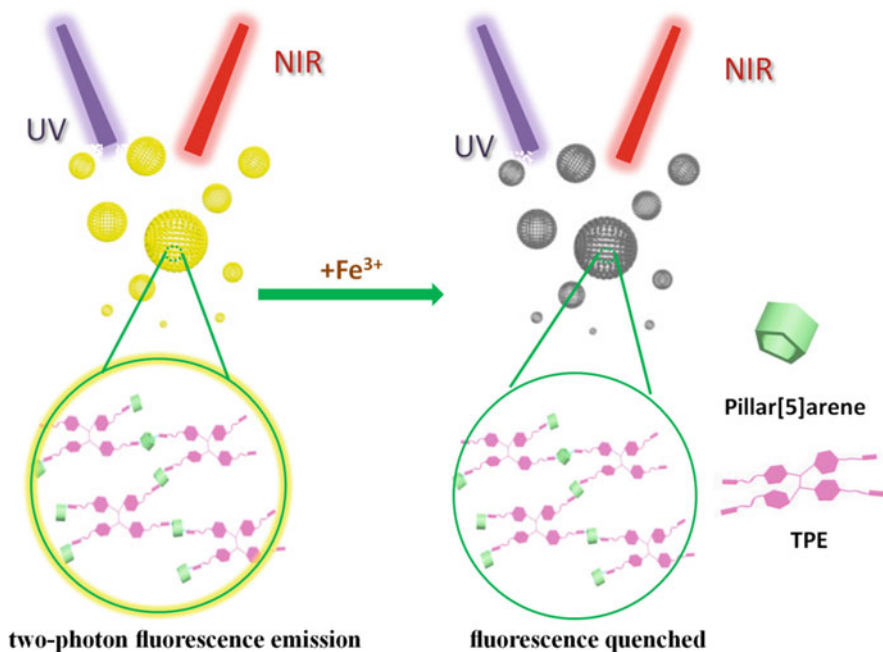


Fig. 19 Schematic illustration of conjugated macrocycle polymer (P[5]-TPE-CMP) based on pillararene and TPE and two-photon fluorescence sensing for Fe³⁺ and organic molecules

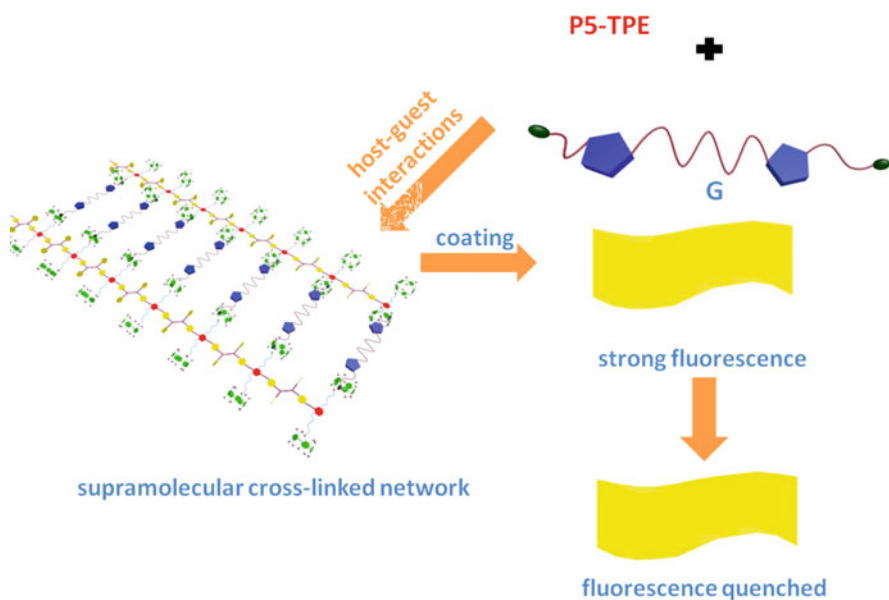


Fig. 20 Schematic illustration of AIEE fluorescent supramolecular cross-linked polymer network by P5-TPE and G

excellent luminescence properties, the constructed supramolecular assemblies have been applied as light-harvesting, white-light materials, 2D luminescence materials, cell imaging, and sensors. Then it could be applied as smart materials and drug delivery due to its dynamic controllability behavior. Although macrocycle-based AIE supramolecular assemblies play an important role in numerous fields, it is still a very challenging task to design and fabricate functional luminescence materials.

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