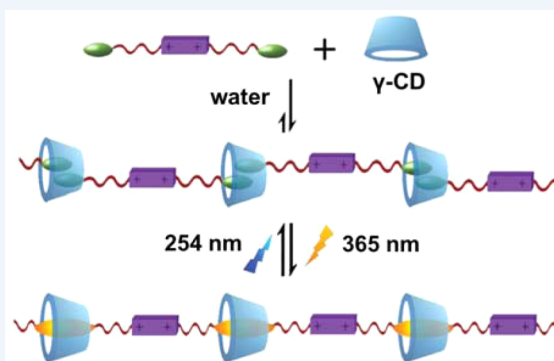# Stimuli-Responsive Supramolecular Polymers in Aqueous Solution

Xiang Ma and He Tian*

Key Laboratory for Advanced Materials and Institute of Fine Chemicals, East China University of Science & Technology, Shanghai 200237, P. R. China

CONSPECTUS: Aiming to construct various novel supramolecular polymeric structures in aqueous solution beyond small supramolecular self-assembly molecules and develop functional supramolecular polymeric materials, research interest on functional supramolecular polymers has been prevailing in recent years. Supramolecular polymers are formed by bridging monomers or components together via highly directional noncovalent interactions such as hydrogen bonding, hydrophobic interaction, $\pi-\pi$ interaction, metal—ligand coordination, electrostatic interaction, and so forth. They can be easily functionalized by employing diverse building components with specific functions besides the traditional polymeric properties, a number of which are responsive to such external stimuli as pH variance, photoirradiation, chemically or electrochemically redox with the controllable con-

formation or construction switching, polymerization building and rebuilding, and function adjustment reversibly owing to the reversibility of noncovalent interactions. Supramolecular polymers are "soft matters" and can be functionalized with specific properties such as morphology adjustment, controllable luminescence, shape memory, self-healing, and so forth. Supramolecular polymers constructed based on macrocycle recognition and interlocked structures represent one typical branch of the supramolecular polymer family. Cyclodextrin (CD), cucurbituril (CB), and hydrophilic calixarene derivatives are usually employed to construct hydrophilic supramolecular polymers in aqueous solution. Stimuli-responsive hydrophilic supramolecular polymers, constructed in aqueous solution particularly, can be promising candidates for mimicking biocompatible or vital functional materials.

This Account mainly focuses on the recent stimuli-responsive supramolecular polymers based on the host—guest interaction in aqueous solution. We describe the hydrophilic supramolecular polymers constructed via hydrophobic effects, electrostatic interaction, metal—ligand coordination, and multiple combinations of the above noncovalent interactions. The disparate ways to engender stimuli-responsive supramolecular polymers via the hydrophobic effects of α-CD, β-CD, and γ-CD macrocycles are illustrated and discussed. Some recent works on CD-based photoresponsive functional supramolecular polymers are summarized. CB (especially CB[8]) based supramolecular polymers and their pH-responsive and photoresponsive properties are introduced. Hydrophilic calixarene derivative (bis(p-sulfonatocalix[4]arene) typically) based supramolecular polymers via electrostatic interactions are reviewed, and their redox-responsive association/disassociation elaborated in detail. More complicate supramolecular polymers based on multiple noncovalent interactions are illustrated including hydrophobic effect, metal—ligand coordination, and electrostatic interactions and their functional stimuli-responsiveness elaborated as well. Finally, we give perspectives on the strength of these diverse noncovalent interactions to form supramolecular polymers in aqueous solution, on the advantage, disadvantage, efficiency, and reversibility of using certain stimuli in constructing supramolecular polymers and prospect the future function improvement of these polymers as functional materials.

1. INTRODUCTION

Supramolecular polymers are constructed generally via holding monomers or components together in macromolecules by highly directional noncovalent interactions such as hydrogen bonding, hydrophobic effects, $\pi-\pi$ interaction, metal—ligand interaction, electrostatic interaction, and so forth.[1−3] The monomeric components, like guest units, host macrocycles, or even simple host—guest inclusion systems, can be modularized and integrated controllably to construct various supramolecular polymers with specific conformations or functions. Different from the conventional polymers provided with stable structures prepared via covalent bonding of repeated monomers and high molecular weights usually over 10^5 Da, supramolecular polymers

are constructed via various noncovalent interactions whose strengths depend on the properties of the mutual interaction species and their molecular weights are usually much smaller. However, supramolecular polymers can be easily functionalized by employing diverse building components with specific functions besides the traditional polymeric properties via various noncovalent interactions. Most interestingly, lots of supramolecular polymers are responsive to such external stimuli as pH variance, photoirradiation, chemically or electrochemically redox

with the controllable conformations or construction switching, and function adjustment reversibly owing to the reversibility of noncovalent interactions.[4] From this point of view, supramolecular polymers might be the optimal artificial systems for mimicking biocompatible or vital functional systems. They are "soft matters" but with certain material strength. Under specific environment or external stimuli, special properties and advantages of supramolecular polymers such as their controllably modularized construction, polymerization building and rebuilding, conformational conversion, self-healing, and so forth can be achieved, which makes them promising candidates for smart materials and biomaterials. Meanwhile, the construction of supramolecular polymers via polymerizing or gathering small supramolecular systems could probably amplify the specific functions of the monomeric supramolecular systems, which was one of the motivations as well.

A number of supramolecular polymers are constructed based on macrocycle recognition and interlocked structures, which represent one typical branch of the supramolecular polymer family. Macrocyclic components such as crown ether, cyclodextrin (CD), cucurbituril (CB), calixarene, pillararene, and their derivatives (Scheme 1) are usually employed as the hosts in the monomers for building supramolecular polymers. These macrocycles are provided with their own structural features and are

Scheme 1. Chemical Structures of the Macrocyclic Hosts Elaborated in This Account

n = 0, α-CD; n = 1, β-CD; n = 2, γ-CD

n = 6, CB[6]; n = 7, CB[7]; n = 8, CB[8]

SC4
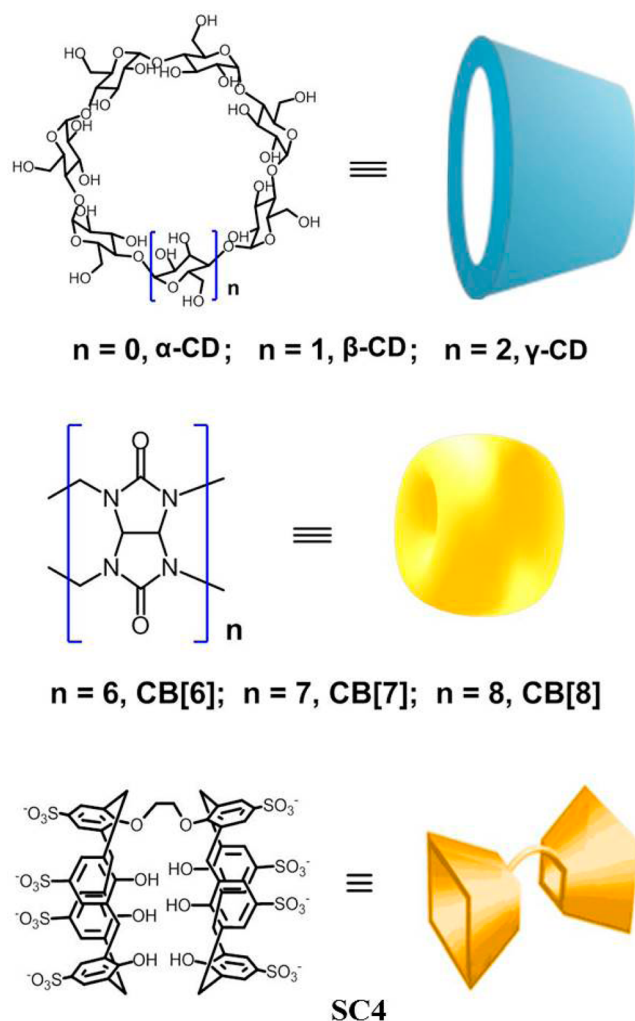
capable of recognizing the specific guest molecules to form pseudorotaxane, rotaxane, or catenane-like inclusion systems. Supramolecular polymers are thus constructed by integrating these building blocks based on host–guest recognition in a modularized way. Among these host species, crown ether,[5,6] hydrophobic calixarene,[7] and pillararene[8] macrocycles are usually employed to construct hydrophobic supramolecular polymers via hydrogen bonding interaction[9] in lower-polarity solvents. While CD, CB, and hydrophilic calixarene (sulfonato-calixarene typically) based supramolecular polymers are formed in aqueous solution. Noteworthy, owing to the stimuli-responsive properties of the host–guest inclusion systems in the monomers, the corresponding supramolecular polymers are also stimuli-responsive, with either the structural building and rebuilding or the adjustment of their macroscopical properties.

In recent years, the development and functionality of supramolecular polymeric materials have been reviewed several times (including but not limited to refs 1−5 and 7) owing to the growing interest of the scientists in the areas of supramolecular chemistry and materials. Among them, stimuli-responsive hydrophilic supramolecular polymers, as a special and important species constructed based on hydrophilic components in aqueous solution, are provided with specific function and regarded as promising candidates for the biocompatible functional materials. In this brief Account, we will mainly focus on the recent stimuli-responsive functional supramolecular polymers in aqueous solution and present some perspectives of their future development as well.

Similar to the noncovalent template-directed strategy to build supramolecular monomers in aqueous solution, supramolecular polymers are constructed from the aqueous media via holding their building blocks together relying on a wide range of supramolecular noncovalent interactions such as hydrophobic effects, electrostatic interaction, metal–ligand coordination, multiple combination of them, and so forth.

2. STIMULI-RESPONSIVE SUPRAMOLECULAR POLYMERS BASED ON HYDROPHOBIC EFFECTS

The hydrophobic effect[10] is the observed tendency of hydrophobic molecules or parts to aggregate in aqueous solution and exclude water molecules, which are widely used to construct supramolecular polymers in such typical hydrophilic macrocyclic hosts and the key components to form supramolecular polymers in aqueous solution as CD and CB based systems. Both of these two hosts are provided with hydrophobic cavities as well as hydrophilic and polar rims as to effectively include specific guest species in aqueous media to form supramolecular polymers. A number of these supramolecular polymers constructed based on hydrophobic effects are responsive to such external stimuli as photo irradiation or pH adjustments acting on the guest components, leading to either the polymeric structure dissociation or conformation variance. In most cases, these responsive processes of supramolecular polymers can be recovered back with another alternative stimulus.

2.1. CD Based Stimuli-Responsive Supramolecular Polymers

Hydrophobic guests such as azobenzene, stilbene, and other stimuli-responsive components are readily to be transferred into the hydrophobic interior of CD macrocycle in aqueous solution.[11] α-CD has the smallest cavity, whose volume matches the regular azobenzene or stilbene best, and can be driven to shuttle on and off these two guest units owing to their conformational photoisomerization.[12,13] While β-CD is readily

decorated with many functional groups[14] and derived into dimer as well, which makes them as very popular candidates of host components in both supramolecular monomeric and polymeric systems. Different from these two homologues in CD family, γ-CD has the bulkiest cavity volume and is capable of including bigger guest units or incorporating two guest moieties together into its cavity. γ-CD based supramolecular monomer is usually consist of more than two components and its supramolecular polymer appears a unique inclusion conformation.

The stimuli-responsive main chain supramolecular polymers based on α-CD or its derivatives were less reported, since α-CD has the smallest cavity so as to include only one guest molecule in its cavity. Moreover, the chemical modification on the rims of α-CD is relatively difficult. An efficient strategy is to connect α-CD macrocycle in the side chains of a covalent polymer and use the whole polymer chain to assemble with another polymer chain incorporating guest molecules in the side chains. Harada et al.[15] reported a light-responsive supramolecular polymer hydrogel obtained from one host polymer containing α-CD macrocycles in the side chains and another guest polymer with azobenzene unites in the side chains. The association and dissociation between the two polymers could be controlled by light irradiation. Later, they synthesized two polyacrylamide-based host polymer hydrogels functionalized with α-CD and β-CD, the guest polymer hydrogel functionalized with azobenzene and the host/guest coexiting hydrogel SP1, respectively (Figure 1).[16]
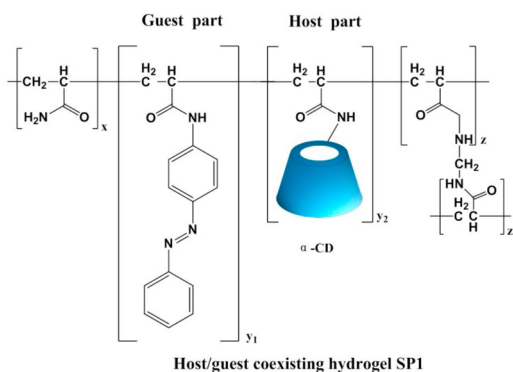

Figure 1. Chemical structure of supramolecular polymer hydrogel SP1.

Physical shaking of the macroscopic host and guest hydrogel pieces in water could induce the obvious and visible gel assembly. All these supramolecular polymer hydrogels were photoresponsive and assembling on the macroscopic scale.

Various supramolecular polymers employing β-CD as host have been constructed to achieve specific stimuli-responsive functions. β-CD possessing a moderate cavity is easy to be modified by functional groups on the narrow rim. Basically there are three strategies to construct β-CD based stimuli-responsive supramolecular polymers. One strategy is using β-CD macrocycles or its derivatives as hosts to assemble with guest polymers to form supramolecular polymers. Another one is incorporating β-CD macrocycles in the side chain of a host polymer and then assembling with guest polymers to form supramolecular polymers. The third one is utilizing β-CD derivatives as building blocks with extensible supramolecular interaction sites to construct supramolecular polymers, in which the guest units are usually covalently connected with β-CD macrocycles. The stimuli-response of the functional groups either connected on the β-CD rims or incorporated in guest blocks thus makes the

constructed supramolecular polymers stimuli-responsive consequently.

We prepared a photoresponsive supramolecular polymer SP2 employing a light-active fluorescent rotor modified β-CD (RCD) as host and α,ω-diaminopoly(propylene glycol)s as guest chain shown in Figure 2.[17] The fluorescent rotor contained a
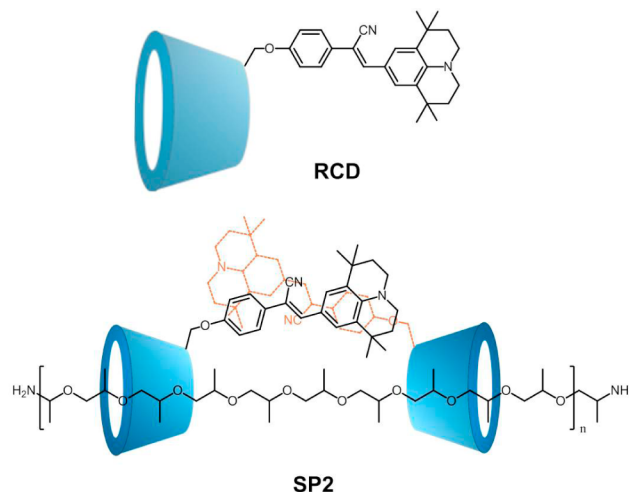

Figure 2. Supramolecular polymer SP2 with fluorescent viscosity sensitivity.

cyanostilbene unit, which could be reversibly photoisomerized by 254 nm UV light and visible light, respectively. RCD showed a good solvent viscosity sensitive behavior due to the environment dependent nonradiative decay. SP2 displayed lockable ratiometric fluorescent viscosity sensitivity. The fluorescent emission engendered by intramolecular excimer of the fluorophores was used to address the concentration of the compound, while the emission corresponding to the rotor fluorescence of the monomers acted as a viscosity sensitive signal and could be shut off by UV irradiation.

Harada et al. developed a redox-responsive supramolecular host−guest polymer SP3,[18] in which a poly(acrylic acid) possessing β-CD macrocycles in the side chains was employed as host polymer chain to mix with another guest polymer containing ferrocene units in the side chains (Figure 3). The assembly of these two host−guest polymers engendered a transparent supramolecular hydrogel based on the inclusion between β-CDs and ferrocene moieties. Oxidation of the hydrogel using NaClO (on the ferrocene units) broke the supramolecular inclusion of β-CD and ferrocene thus inducing a phase transition into the solution state. Reversibly, continuous addition of glutathione recovered the elasticity to yield the hydrogel. This reversible process could also be realized by electrochemical redox reactions.

γ-CD, with the biggest cavity in CD family, is capable of including relatively bigger guest molecule than β-CD or two moderate guest molecules together in its cavity. It thus supplies a new strategy to construct supramolecular polymer in which γ-CD host works as a connecting junction to form a ternary complex by including two moieties belonging to different guest building blocks inside. Most γ-CD based supramolecular polymers have been built in this way. Usually, the response of the units included in γ-CD cavity to external stimuli makes the whole supramolecular polymer provided with stimuli-responsive function.

Recently, we reported the first dual-modality photoswitchable supramolecular polymer SP4 as a kind of advanced functional
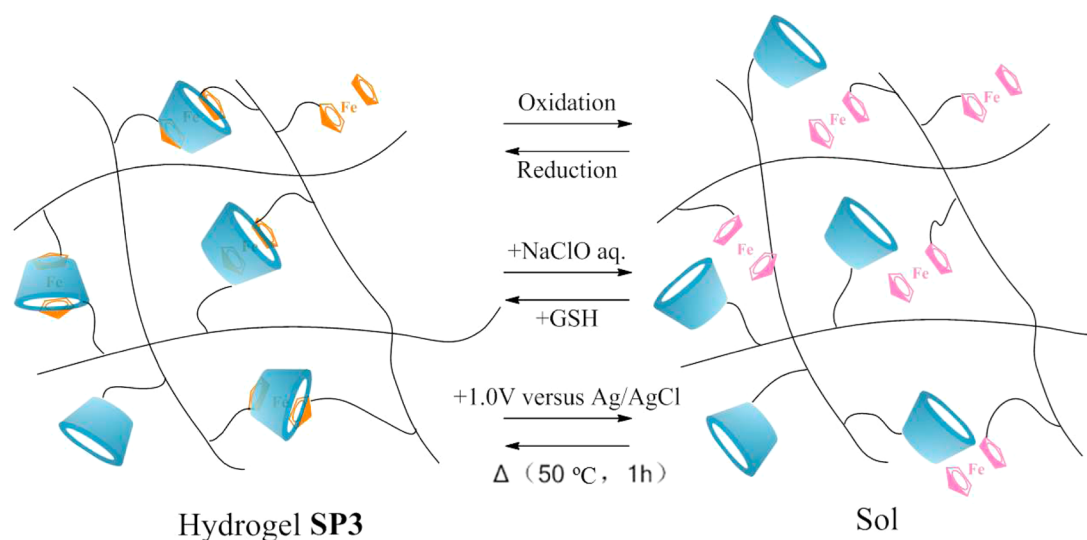
Figure 3. Hydrogel SP3 and its redox-responsive sol–gel transition.

material,[19] which can be switched between a noncovalent polymer and its corresponding covalent polymer CP4 in response to external light stimuli by taking advantages of the reversible photodimerization of coumarins and host–guest assemblies with γ-CD. As shown in Figure 4, the monomer
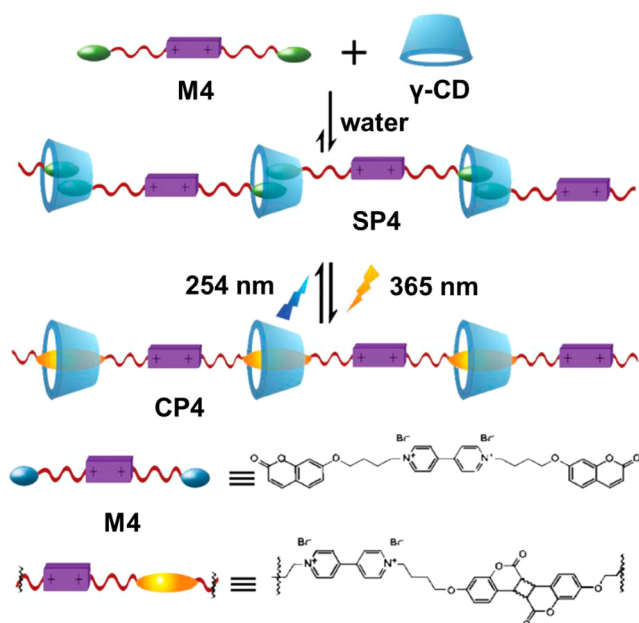

Figure 4. Chemical structures of the supramolecular noncovalent polymer SP4 and its reversible photoswitchable conversion to covalent polymer CP4.

M4, bearing two terminal coumarins connected by a viologen moiety, could form a supramolecular noncovalent polymer SP4 with γ-CD in aqueous solution due to the fact that the γ-CD accommodated two coumarin moieties inside its large hydrophobic cavity. Upon irradiation with UV light at 365 nm, SP4 can be converted into its corresponding covalent polymer CP4 with a covalent polymer backbone by the way that the irradiation engendered highly efficient photoinduced cyclodimerization of coumarin units and generated a stable cyclobutane-based dimer in the cavity of γ-CD. Reversibly, the conversion from CP4 back

to SP4 could be achieved via alternative UV light irradiation at 254 nm, which led to the photochemical cleavage of the dimer. However, the monomer M4 could hardly generate the photoinduced cyclodimerization reaction of coumarin moieties alone under UV light irradiation at 365 nm, even at a high concentration in aqueous solution. Therefore, the γ-CD macrocycle here played a key role as microreactor for the photodimerization of coumarin units and the reversed photo-cleavage of the cyclobutane-based dimers.

This unusual material can go from a supramolecular polymer to a covalent polymer and back again with the light irradiation. The substances with switchable properties can combine advantages of distinct polymers in a single platform.[20] Moreover, the dual-modality photoswitching between a noncovalent supramolecular polymer and a covalent polymer might supply an effective way to further increase the molecular weight of polymers. It also could be employed to confirm and characterize the precise structure of supramolecular polymers thus to promisingly overcome the dilemma that the precise structural characterization of most supramolecular polymers was usually a challenge.[21]

Based on this feasibility of photoswitchable conversion between a γ-CD based noncovalent supramolecular polymer and its covalent form above, we constructed another netlike γ-CD based supramolecular polymer, whose linkages among different units could be photoswitchable noncovalently and covalently.[22] As shown in Figure 5, the guest building block of the supramolecular polymer SP5 was a tribranched monomer M5 containing one viologen and one coumarin moiety in each arm. The three viologen moieties in the three arms of M5 supplied such a good water solubility of the monomer as to make M5 readily included by γ-CD on coumarin units. By taking advantage of 2:1 host–guest self-assembly between courmarin moieties and γ-CD, the noncovalently linked netlike supramolecular polymer SP5 was constructed. With the same mechanism as SP4, SP5 could be converted into its corresponding reticulate poly-catenane-like structure CP5 with a covalent polymer backbone upon irradiation with UV light at 365 nm, in which the light irradiation induced the cyclodimerization of coumarin units and engendered a stable cyclobutane based dimer in the cavity of γ-CD. Interestingly, when supramolecular polymer SP5 became CP5 under UV irradiation, the viscoelasticity of its aqueous
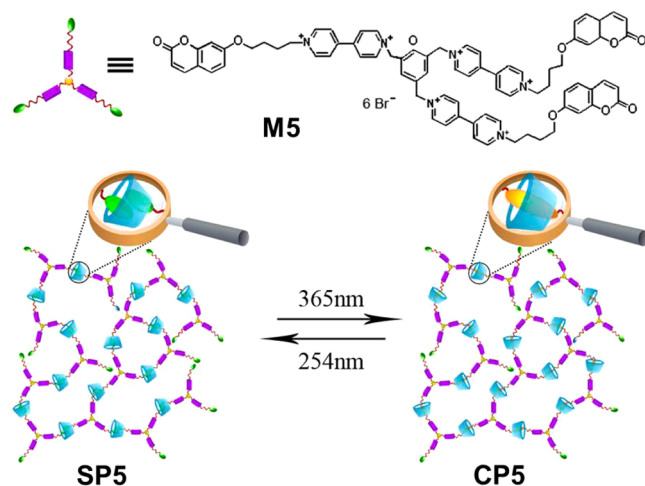
Figure 5. Supramolecular noncovalent linked netlike polymer SP5 and the photoswitching between SP5 and its corresponding covalent polymer CP5 by alternating UV light irradiations.

solution dramatically increased as to engender a hydrogel system from solution without additional gelators. This CP5 hydrogel could be converted back into SP5 solution either by heating to 60 °C or irradiation with UV light at 254 nm. It was a thermally and photochemically dual-responsive supramolecular polymer.

2.2. CB Based Stimuli-Responsive Supramolecular Polymers

Cucurbit[*n*]urils (CB[*n*]s) can usually include cationic guest molecules inside their hydrophobic cavities to form host–guest complex with very high binding constants in aqueous solution.[23,24] The ion dipole and hydrogen bonding interactions between their carbonyl portals and the guests also exist in the CB based supramolecular systems. However, chemical modification of CBs are usually so difficult that the supramolecular polymers based on CB[5], CB[6], and CB[7] are rare.[25] Some mechanical interlocked molecules incorporating CB[6] as a molecular "bead" and their supramolecular assemblies as 1D, 2D, and 3D polyrotaxanes with high structural regularity have been achieved.[26] In recent years, the CB[8] host is employed to construct supramolecular polymers on account of the fact that it is provided with a bigger cavity in CB family and able to include two guest moieties inside. In these supramolecular polymers, the CB[8] complex, usually including two moieties belonging to the same or alternative monomers together via enhanced charge-transfer (CT) interactions, plays the role of a connecting junction among the repeated monomers.[27] Zhang et al. proposed a "dimer in dimer" strategy and constructed several CB[8] based supramolecular polymers.[28,29] Scherman reported several polymers with terminal electron-donating or electron-accepting groups jointed together inside the cavity of CB[8] to form supramolecular polymers.[30,31]

CB based supramolecular complexes are usually responsive to external pH variance or the competitive threading of alternative guests; thus, many supramolecular polymers employing CBs as hosts can respond to the pH stimulus. Besides pH variance, other sort of stimulus was also employed to make CB host based supramolecular polymer responsive. Recently, Scherman et al. reported a CB-based supramolecular complex responsive to light stimulus.[32] As shown in Figure 6, the monomer M6 has two hydrophilic viologen units in the middle and another two azobenzene moieties at the two ends. It could be included by CB[8] to form supramolecular polymer SP6 by the way that one
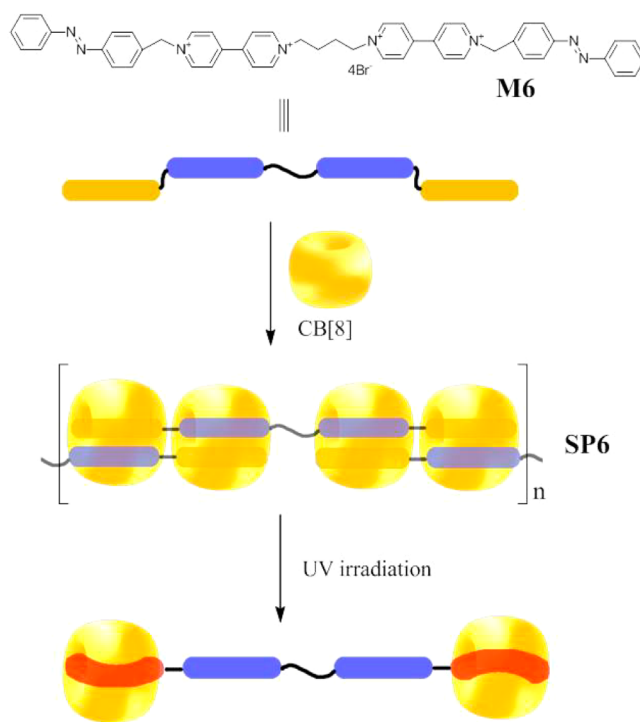

Figure 6. CB[8] based supramolecular polymer SP6 and its photo-controlled conversion.

azobenzene unit of M6 and one viologen moiety of another M6 molecule were embedded in the cavity of CB[8] together. The photoinduced complexation/decomplexation process of the formed supramolecular polymer SP6 could be realized reversibly owing to the reversible photoisomerization of the azobenzene units. Zhang and co-workers developed another covalently attached hyperbranched polymer via photoresponsive supramolecular polymerization.[33] A three-arm photosensitive monomer M7 containing three azastilbene units was synthesized as seen in Figure 7. After mixing CB[8] with M7 in a molar ratio of 3:2, a photosensitive supramolecular hyperbranched polymer SP7 could be formed through host–guest interaction between CB[8] and two azastilbene moieties, respectively, belonging to different M7 monomer. This supramolecular hyperbranched polymer could be converted into covalently attached hyper-branched one due to the fact that the [2 + 2] cycloaddition of C═C bonds of azastilbene could occur in the cavity of CB[8] upon UV irradiation.

3. STIMULI-RESPONSIVE SUPRAMOLECULAR POLYMERS BASED ON ELECTROSTATIC INTERACTIONS

Noncovalent electrostatic interaction between host and guest building blocks was also employed to construct supramolecular polymers in aqueous solution. The macrocyclic hosts and the guests building blocks are usually functionalized with anions (like sulfonate and carboxylate units) and cations (like quaternary ammonium moieties) groups, respectively, as their supramolecular interaction sites. Macrocyclic calixarene derivatives are usually employed to construct supramolecular polymers based on such electrostatic interactions.

Modification of calixarene with hydrophilic groups on its rims can improve its hydrophility in aqueous media. For example, water-soluble *p*-sulfonatocalixarene hosts are of strong binding
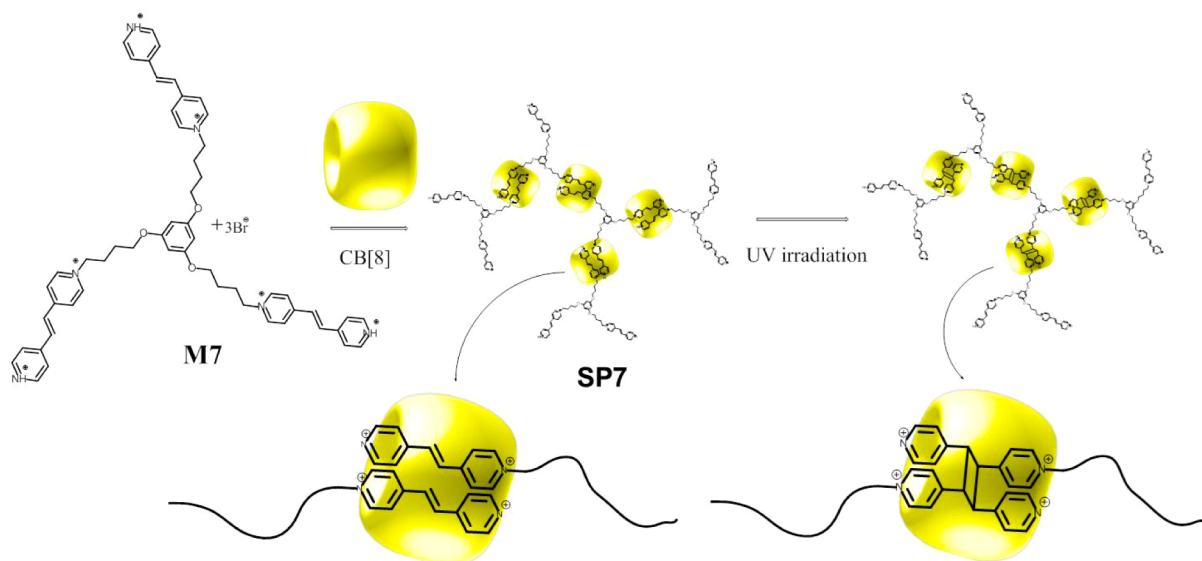
Figure 7. Structures and the transformation from noncovalently attached supramolecular hyperbranched polymer SP7 to covalently attached one by UV irradiation.

affinity toward organic cations via the synergistic inclusion properties of the sulfonic groups. The homoditopic bis(p-sulfonatocalix[5]arene) (SC5) and bis(p-sulfonatocalix[4]-arene) (SC4) bridged at their smaller rims were prepared as macrocyclic hosts to construct supramolecular polymers. Two supramolecular polymers with 2D netlike and 1D linear topological structures were constructed by employing SC5 as host components and tetracationic and dicationic porphyrins as guest components, respectively.[34]

When the guest building blocks were responsive to external stimuli, such as redox of connecting cation units and protonation/deprotonation of the interaction moieties, the calixarene based supramolecular polymers became responsive consequently. Liu et al. reported a supramolecular polymer SP8 employing SC4 as host macrocycle and ethylene-bridged bis(viologens) as guest M8, as shown in Figure 8.[35] The iterative complexation of SC4 with M8 via electrostatic interaction between the sulfonate anions of SC4 and the cations of M8 engendered a linear supramolecular polymer. SP8 was responsive to the electrochemical stimulus since the assembly/disassembly of the supramolecular polymer could be controlled reversibly by
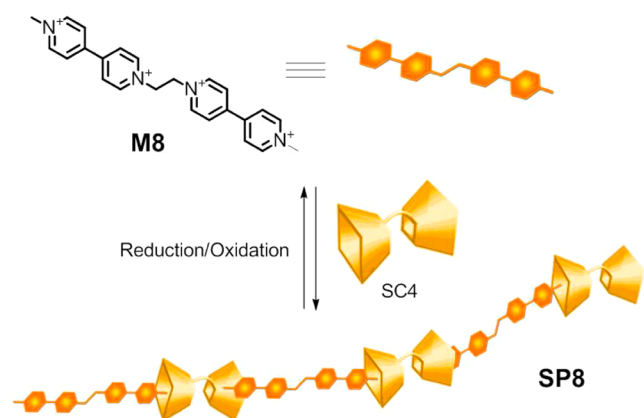
the electrochemical redox switching, accompanying with its complexation stability decrease due to the fact that the redox-sensitive viologen changed reversibly from dicationic to radical cationic, to neutral forms successively.

We constructed an electrochemical and pH dual stimuli-responsive supramolecular polymer SP9 in aqueous media based on the SC4 host.[36] SP9 was formed from two complementary monomers which contain SC4 and a homoditopic M9 receptor with both viologen and dimethylamino connectors decorated with a fluorophore (Figure 9). This fluorescent supramolecular polymer could reversibly respond to both electrochemical redox and pH variance, allowing the two kinds of pseudorotaxanes formed as unimers to be induced by respective stimuli. SC4 and viologen could form host−guest electrostatic pairs because of their high complexation stability, and the dimethylamino moiety could also bind with SC4 with high association constant after protonation. The dimethylamino unit could hardly associate with SC4 before protonation. Moreover, the complex constant of viologen and SC4 was dramatically sensitive to the redox process of viologen, which ensured the reversible assembly/disassembly process between them. Supramolecular polymer SP9 was a redox and pH dual-responsive one, whose assembly and disassembly into two pseudorotaxane monomers could be manipulated reversibly via both electrochemical redox and protonation/deprotonation accompanying with obvious and disparate fluorescent emission.

Some supramolecular polymers, constructed based on electrostatic interactions of hydrophilic calixarene with guests in aqueous solution, contained more than one macrocyclic host, whose building blocks were already supramolecular complexes themselves. These supramolecular polymers responsive to external stimuli were usually more sophisticated, well-designed and provided with more specific functions.

We collaborated with Prof. Li and reported a light-driven linear helical supramolecular polymer SP10 constructed via host−guest electrostatic interaction between SC4 and an α-CD based pseudo[3]rotaxane R containing axially chiral binaphthyl and azobenzene moieties,[37] as shown in Figure 10A. The binaphthyl unit in the guest building block M10 was employed for engendering the charity, the azobenzene moiety for being

Figure 8. Redox responsive supramolecular polymer SP8 formed by the iterative complexation between SC4 and M8.
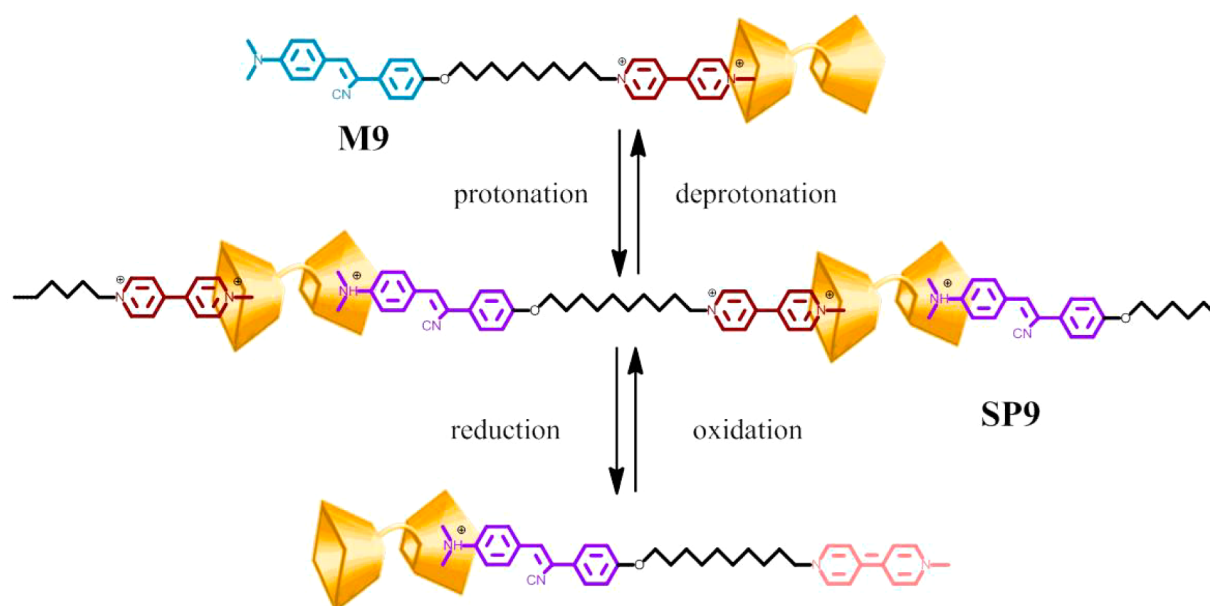
Figure 9. Reversible assembly/disassembly of supramolecular polymer SP9 induced by the respective stimuli of protonation/deprotonation and electrochemical redox.
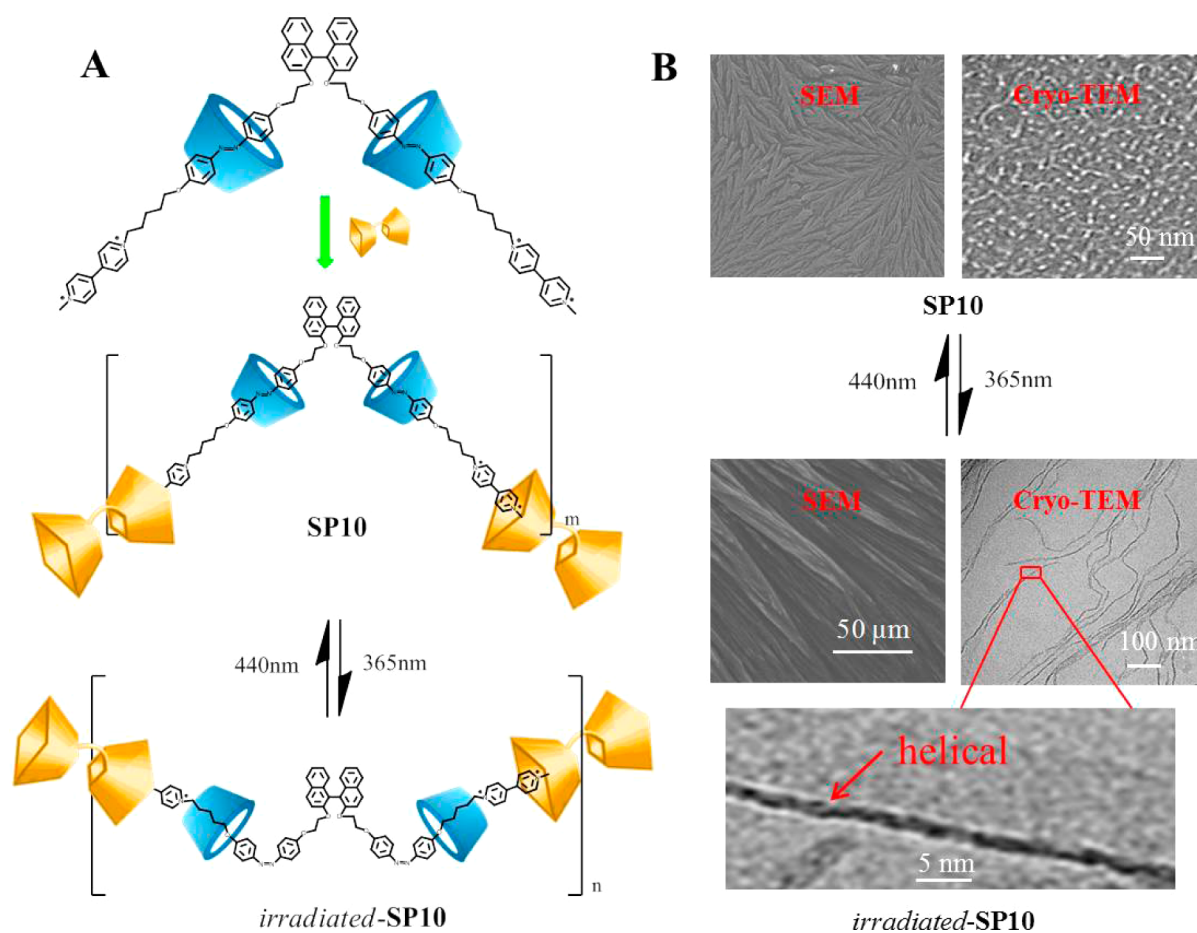

Figure 10. (A) Supramolecular polymer SP10 formed via the self-assembly between SC4 and an α-CD pseudo[3]rotaxane, and its photoresponsiveness by alternative UV irradiations. (B) SEM and cryo-TEM images of SP10 and irradiated-SP10.

included by α-CD, and the viologen for not only improving the hydrophilicity but also binding with SC4. M10 was first included by two α-CD macrocycles onto the two *trans*-azobenzene sites to form a pseudo[3]rotaxane. After mixing equivalent SC4 with the pseudo[3]rotaxane in aqueous solution, a supramolecular polymer SP10 was formed via the electrostatic interaction
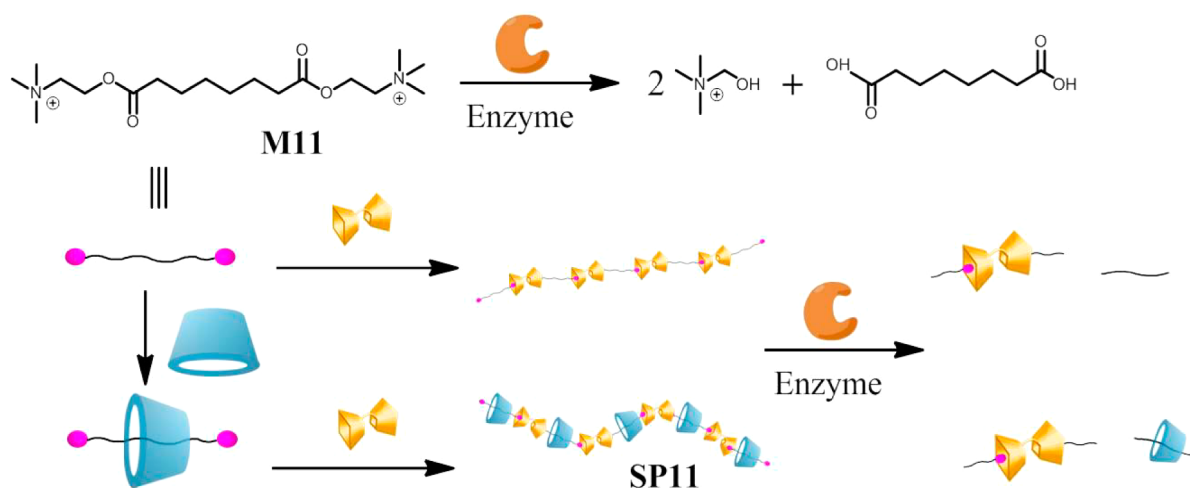
Figure 11. Supramolecular ternary polymer SP11 with two orthogonal host−guest interactions.
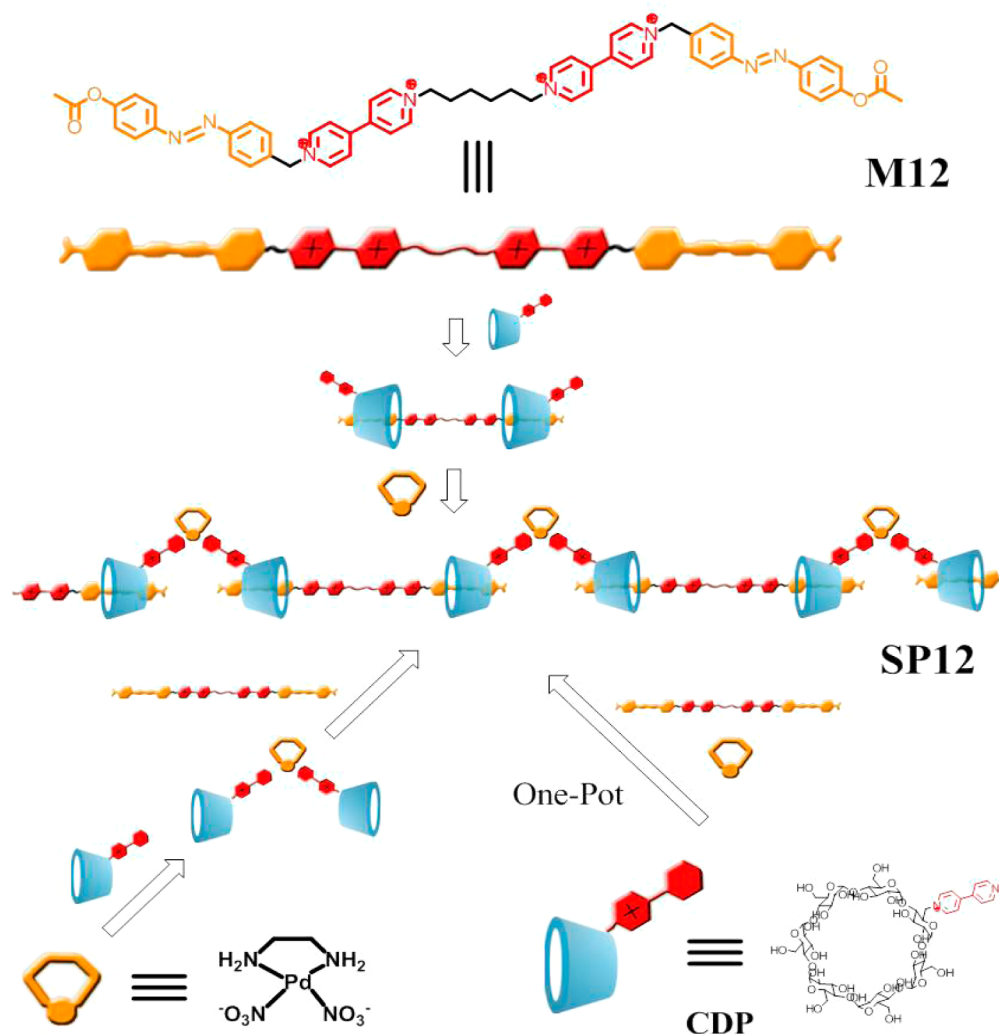

Figure 12. Supramolecular polymer SP12 based on multiple noncovalent interactions.

between SC4 and the terminal viologen moieties of building blocks R. This supramolecular polymer SP10 was provided with chirality showing an obvious starlike morphology with multiple branches in its scanning electron microscopy (SEM) images and netlike image in its cryogenic transmission electron microscopy

(cryo-TEM) image (Figure 10B). While upon UV irradiation with 365 nm light, the morphology of the supramolecular polymer irradiated-SP10 changed significantly exhibiting linear belts in SEM image and linear helical belts in cryo-TEM image. Interestingly, the single linear helical supramolecular polymer
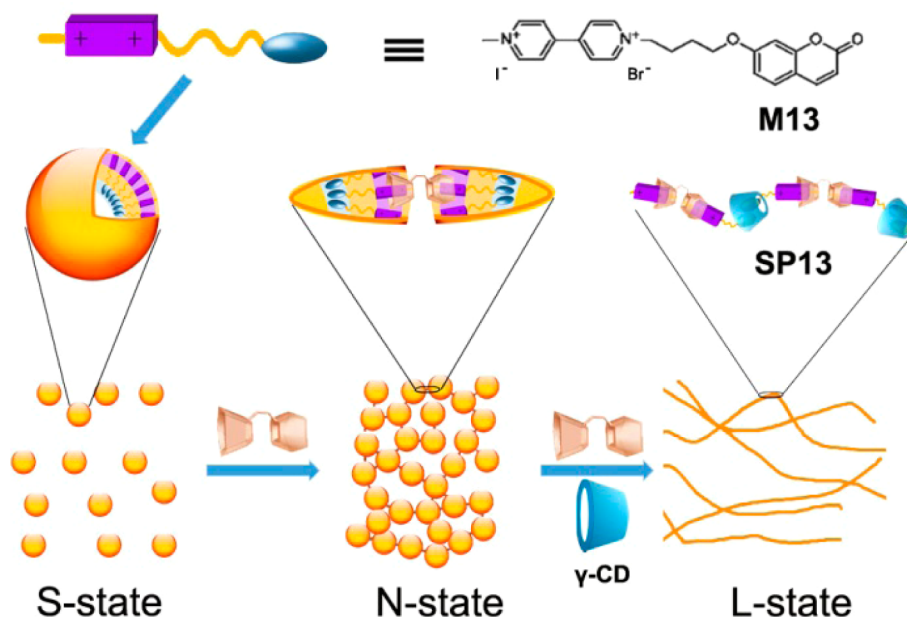
Figure 13. Formation of the supramolecular polymer SP13 with corresponding morphology transition controlled by host−guest interactions.

irradiated-SP10 with a diameter of ca. 2 nm and a length of hundred nanometers to micrometers in aqueous solution was clearly observed (the calculated width of monomer M10 was about 1.6 nm). This could be attributed that irradiated-SP10 containing *cis*-azobenzene units had a more straight conformation comparing with SP10 provided with *trans*-azobenzene moieties, engendering the formation of linear supramolecular polymer. Different from other linear supramolecular polymers whose observed morphologys were induced from the assembly, intramolecular or intermolecular interaction of multiple polymeric lines, this observed helicity by cryo-TEM of the linear single supramolecular polymer SP10 originated from its intrinsic property rather than external supramolecular induction effect. This is the first example of photoresponsive supramolecular polymer with single linear helical supramolecular structure, whose morphology adjustment of its intrinsic state was directly observed via cryo-TEM measurements.

Liu et al. reported an enzyme-responsive supramolecular polymer SP11 by complexation of SC4 with suberyl dicholine M11 based pseudorotaxane.[38] As shown in Figure 11, M11 was employed as the axle of SP11, α-CD as the threading wheel, and SC4 macrocycle as the iterative end-capping unit. The formed supramolecular polymer assembly was capable of dispersal by an enzymatic reaction owing to the hydrolysis of M11 by cholinesterases. This novel sort of stimulus by enzyme approach was provided with inherent biocompatibility, mild conditions, high efficiency and specificity for the disassembly responsiveness of the supramolecular polymer.

4. STIMULI-RESPONSIVE SUPRAMOLECULAR POLYMERS BASED ON MULTIPLE NONCOVALENT INTERACTIONS

Supramolecular polymers with more complicated structures, formed by employing multiple host or guest components, or based on multiple noncovalent interactions, or provided with multiple stimuli-responsiveness to achieve specific functions, were also well designed and constructed. We synthesized several low molecular weight monomers for supramolecular polymerization.[39] A rodlike guest compound M12 containing two

azobenzene units, able to be well encapsulated by β-CD macrocycle or its derivative CDP via hydrophobic host−guest interaction, in the two ends connected by two viologen moieties as hydrophilic electropositive barriers was designed and prepared (Figure 12). Based on these two facts that M12 and ethylenediamine palladium(II) nitrate (enPd) could be associated noncovalently with CDP via hydrophobic inclusion and metal−ligand coordination interactions, respectively, a supramolecular polymer SP12 could be formed via two routes for stepwise self-assemblies. As seen in Figure 12, one route began with the host−guest binding between M12 and CDP followed by metal−ligand coordination with enPd, while the other one following the reverse sequence of these two self-assembly behaviors. Also, a one pot route via directly mixing M12, enPd, and CDP together could also engender the very supramolecular polymer SP12. This supramolecular polymer could be responsive to light irradiation owing to the photo-isomerization of the main chain containing azobenzene moieties. The construction of SP12 involving three routes provided a new synthesis methodology for design and formation of new smart responsive supramolecular copolymers.

Another supramolecular polymer employing both CB[8] host-stabilized CT interaction and SC4 electrostatic interaction was constructed in our group, in which two disparate pseudorotaxanes were used as relevant monomers.[40] The rodlike guest molecule contains both a viologen electron-acceptor and another fluorescent dimethylaminodiphenylvinyl electron-donor. A high polymerized supramolecular polymer could be engendered based on the CB[8] stabilized CT interaction by encapsulating a viologen unit and another fluorophore moiety together inside CB[8] cavity to form a stable intermolecular CT complex. Both the reversible protonation/deprotonation of the dimethyl decorating donor and the reversible reduction/oxidation of viologen acceptor could broke the CT complex inside CB[8], thus engendered the disassociation of the supramolecular polymer, resulting in two disparate pseudo[2]rotaxane and pseudo[3]rotaxane monomers, respectively. Moreover, mixing SC4 with pseudo[3]rotaxane monomer could form another

supramolecular polymer owing to the strong electrostatic interaction between SC4 and the protonated dimethyl moiety.

The process to form supramolecular polymer via adding alternative macrocyclic hosts or introducing specific stimuli may engender the morphology transition of the supramolecular assembly, which provides the supramolecular polymer with specific functions.[41] We prepared an amphiphilic guest M13 consisting of a hydrophilic viologen unit and a hydrophobic coumarin moiety connected by an alkyl chain shown in Figure 13. The alternative macrocyclic host manipulated sequent micromorphology transition was achieved. In aqueous solution, M13 could form spherical micelle (S-state) itself above the critical micelle concentration (CMC), showing visible spheres in its TEM image. Interestingly, the addition of small amount of SC4 (about 0.1 equiv) connected the micelles to a large scale randomly as to transform the spherical morphology to amorphous wormlike network (N-state) clearly visible in its TEM image as well. This transition was due to the supramolecular electrostatic interaction between SC4 and the viologen on the outer surface of the micelles. Continuing addition of SC4 (up to 0.5 equiv) and subsequent γ-CD (0.5 equiv) finally engendered the linear supramolecular polymer SP13 (L-state) owing to the 2:1 hydrophobic complexation of coumarin moiety and γ-CD.[42] This investigation represented a simple yet efficient approach to control the morphology of multicomponent self-assembly systems.

5. CONCLUSIONS AND PERSPECTIVES

The recent development of stimuli-responsive supramolecular polymers in aqueous solution and their functionality have been reviewed in this Account. Supramolecular polymers can show the traditional polymeric properties, although the molecular weights of them are usually smaller than the traditional ones and the noncovalent interactions to form supramolecular polymers are relatively weaker. The hydrophilic supramolecular polymers are formed in aqueous solution mainly via hydrophobic effect, ion—dipole interaction and electrostatic interaction. However, the hydrogen bonding and metal—ligand coordination interactions are employed much less in water. The ion—dipole interaction and electrostatic interaction are usually much stronger than the hydrophobic effect to form more stable supramolecular polymers in aqueous solution. What's most interesting properties for supramolecular polymers are that the monomer of them can be diversified and involve various functional units with fluorescent emission, adjustable absorption, chirality, redox-feasibility, hydrophobicity, hydrophility, and so forth. And the supramolecular polymers are easy to be controllably responsive to external stimuli such as alternative light-irradiation, chemical or electrochemical redox, pH variance, heating and cooling, and so forth. Usually, light-irradiation is convenient, environmentally friendly, and fast-responsive but hardly reaches 100% efficiency. The high efficiency photochemical process would be next challenge for exploration. Chemical redox and pH variance are provided with high efficiency but easily engender waste in the system. Electrochemical redox demands the system conductive or in the conductive circle. While heating and cooling stimuli only apply to limited systems despite being environmentally friendly and having easy operation. In most cases, the stimuli-responsive processes of supramolecular polymers are reversible.

Construction of hydrophilic supramolecular polymers in aqueous solution also aims to develop new polymeric materials besides constructing fascinating supramolecular structures. Cyclodextrin and cucurbituril based supramolecular polymer hydrogels, as new special soft materials, have been reported, some of which were provided with self-healing and shape-memory properties. It should be noted that hydrophilic supramolecular polymers would be developed as promising biocompatible materials in the future, although their supramolecular structures still need be well designed and macroscopical properties such as machinability enhanced.

Presently, most supramolecular polymers in aqueous solution are mainly constructed via the macrocycle recognition or host—guest inclusions. Both novel concepts and effective methodology still need be proposed and developed to control the supramolecular structures of the polymers and to address their precise characterization. Moreover, the related dynamic study is still less during the process of supramolecular polymerization. Developing novel supramolecular polymers toward diverse applicable functionality, especially as self-healing soft materials,[43,44] is a very interesting trend for the future.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: tianhe@ecust.edu.cn.

Notes

Biographies

Xiang Ma was born in China in 1980. He obtained his B.S. degree from Tianjin University in 2003 and Ph.D. in applied chemistry in 2008 from East China University of Science and Technology (ECUST) under the supervision of Prof. He Tian. From January 2011 to July 2012, he worked as a research associate in Liquid Crystal Institute, Kent State University. He is now an associate professor at ECUST, and his current research interests focus on controllable functional supramolecular machines and polymers.

He Tian was born in China in 1962. In 1999, he was appointed Cheung Kong Distinguished Professor by the Education Ministry of China. In 2011, he was selected as a member of the Chinese Academy of Science. In 2013, he became a Fellow of the TWAS—the World Academy of Science—for the advancement of science in developing countries. His current research interests include the supramolecular machines and switches, the synthesis of novel functional organic dyes, and the development of interdisciplinary materials science that determines the electronic and optical properties of materials.

■ ACKNOWLEDGMENTS

■ REFERENCES

(1) Brunsveld, L.; Folmer, J. B.; Meijer, E. W.; Sijbesma, R. P. Supramolecular polymers. *Chem. Rev.* **2001**, *101*, 4071−4098.

(2) Aida, T.; Meijer, E. W.; Stupp, S. I. Functional Supramolecular polymers. *Science* **2012**, *335*, 813−817.

(3) De Greef, T. F. A.; Smulders, M. M. J.; Wolffs, M.; Schenning, A. P. H. J.; Sijbesma, R. P.; Meijer, E. W. Supramolecular polymerization. *Chem. Rev.* **2009**, *109*, 5687−5754.

(4) Yan, X.; Wang, F.; Zheng, B.; Huang, F. Stimuli-responsive supramolecular polymeric materials. *Chem. Soc. Rev.* **2012**, *41*, 6042−6065.

(5) Zheng, B.; Wang, F.; Dong, S.; Huang, F. Supramolecular polymers constructed by crown ether-based molecular recognition. *Chem. Soc. Rev.* **2012**, *41*, 1621−1636.

(6) Bruns, C. J.; Stoddart, J. F. Molecular machines muscle up. *Nat. Nanotechnol.* **2013**, *8*, 9−10.

(7) Guo, D.-S.; Liu, Y. Calixarene-based supramolecular polymerization in solution. *Chem. Soc. Rev.* **2012**, *41*, 5907−5921.

(8) Xue, M.; Yang, Y.; Chi, X.; Zhang, Z.; Huang, F. Pillararenes, a new class of macrocycles for supramolecular chemistry. *Acc. Chem. Res.* **2012**, *45*, 1294−1308.

(9) Fathalla, M.; Lawrence, C. M.; Zhang, N.; Sessler, J. L.; Jayawickramarajah, J. Base-pairing mediated non-covalent polymers. *Chem. Soc. Rev.* **2009**, *38*, 1608−1620.

(10) Chandler, D. Interfaces and the driving force of hydrophobic assembly. *Nature* **2005**, *437*, 640−647.

(11) Wenz, G.; Han, B. H.; Müller, A. Cyclodextrin rotaxanes and polyrotaxanes. *Chem. Rev.* **2006**, *106*, 782−817.

(12) Ma, X.; Tian, H. Bright functional rotaxanes. *Chem. Soc. Rev.* **2010**, *39*, 70−80.

(13) Ma, X.; Wang, Q.; Qu, D.; Tian, H. A light-driven pseudo[4]-rotaxane encoded by induced circular dichroism in hydrogel. *Adv. Funct. Mater.* **2007**, *17*, 829.

(14) Ma, X.; Qu, D.; Ji, F.; Wang, Q.; Zhu, L.; Xu, Y.; Tian, H. A light-driven [1]rotaxane via self-complementary and suzuki-coupling capping. *Chem. Commun.* **2007**, 1409−1411.

(15) Tamesue, S.; Takashima, Y.; Yamaguchi, H.; Shinkai, S.; Harada, A. Photoswitchable supramolecular hydrogels formed by cyclodextrins and azobenzene polymers. *Angew. Chem., Int. Ed.* **2010**, *49*, 7461−7464.

(16) Yamaguchi, H.; Kobayashi, Y.; Kobayashi, R.; Takashima, Y.; Hashidzume, A.; Harada, A. Photoswitchable gel assembly based on molecular recognition. *Nat. Commun.* **2012**, *3*, 603−607.

(17) Zhu, L.-L.; Li, X.; Ji, F.-Y.; Ma, X.; Wang, Q.-C.; Tian, H. Photolockable ratiometric viscosity sensitivity of cyclodextrin polypseudorotaxane with light-active rotor graft. *Langmuir* **2009**, *25*, 3482−3486.

(18) Nakahata, M.; Takashima, Y.; Yamaguchi, H.; Harada, A. Redox-responsive self-healing materials formed from host−guest polymers. *Nat. Commun.* **2011**, *1*, 511−516.

(19) Zhang, Q.; Qu, D.-H.; Wu, J.; Ma, X.; Wang, Q.; Tian, H. A dual-modality photoswitchable supramolecular polymer. *Langmuir* **2013**, *29*, 5345−5350.

(20) Research Highlights. *Nature*, **2013**, *498*, 141.

(21) Liu, Y.; Wang, Z.; Zhang, X. Characterization of supramolecular polymers. *Chem. Soc. Rev.* **2012**, *41*, 5922−5932.

(22) Zhang, Q.; Qu, D.-H.; Ma, X.; Tian, H. Sol−gel conversion based on photoswitching between noncovalently and covalently linked netlike supramolecular polymers. *Chem. Commun.* **2013**, *49*, 9800−9802.

(23) Lee, J. W.; Samal, S.; Selvapalam, N.; Kim, H. J.; Kim, K. Cucurbituril homologues and derivatives: new opportunities in supramolecular chemistry. *Acc. Chem. Res.* **2003**, *36*, 621−630.

(24) Lagona, J.; Mukhopadhyay, P.; Chakrabarti, S.; Isaacs, L. The cucurbit[n]uril family. *Angew. Chem., Int. Ed.* **2005**, *44*, 4844−4870.

(25) Ooya, T.; Inoue, D.; Choi, H. S.; Kobayashi, Y.; Loethen, S.; Thompson, D. H.; Ko, Y. H.; Kim, K.; Yui, N. pH-responsive movement of cucurbit[7]uril in a diblock polypseudorotaxane containing dimethyl α-cyclodextrin and cucurbit[7]uril. *Org. Lett.* **2006**, *8*, 3159−3162.

(26) Kim, K. Mechanically interlocked molecules incorporating cucurbituril and their supramolecular assemblies. *Chem. Soc. Rev.* **2002**, *31*, 96−107.

(27) Liu, Y.; Yang, H.; Wang, Z.; Zhang, X. Cucurbit[8]uril-based supramolecular polymers. *Chem.—Asian J.* **2013**, *8*, 1626−1632.

(28) Liu, Y. L.; Yu, Y.; Gao, J.; Wang, Z. Q.; Zhang, X. Water-soluble supramolecular polymerization driven by multiple host-stabilized charge-transfer interaction. *Angew. Chem., Int. Ed.* **2010**, *49*, 6576−6579.

(29) Fang, R. C.; Liu, Y. L.; Wang, Z. Q.; Zhang, X. Water-soluble supramolecular hyperbranched polymers based on host-enhanced π−π interaction. *Polym. Chem.* **2013**, *4*, 900−903.

(30) Rauwald, U.; Scherman, O. A. Supramolecular block copolymers with cucurbit[8]uril in water. *Angew. Chem., Int. Ed.* **2008**, *47*, 3950−3953.

(31) Loh, X. J.; del Barrio, J.; Toh, P. P. C.; Lee, T. C.; Jiao, D. Z.; Rauwald, U.; Appel, E. A.; Scherman, O. A. Triply triggered doxorubicin release from supramolecular nanocontainers. *Biomacromolecules* **2012**, *13*, 84−91.

(32) Del Barrio, J.; Horton, P. N.; Lairez, D.; Lloyd, G. O.; Toprakcioglu, C.; Scherman, O. A. Photocontrol over cucurbit[8]uril complexes: stoichiometry and supramolecular polymers. *J. Am. Chem. Soc.* **2013**, *135*, 11760−11763.

(33) Yang, H.; Ma, Z.; Wang, Z.; Zhang, X. Fabricating covalently attached hyperbranched polymers by combining photochemistry with supramolecular polymerization. *Polym. Chem.* **2014**, *5*, 1471−1476.

(34) Guo, D.-S.; Chen, K.; Zhang, H.-Q.; Liu, Y. Nano-supramolecular assemblies constructed from water-soluble bis(calix[5]arenes) with porphyrins and their photoinduced electron transfer properties. *Chem.—Asian J.* **2009**, *4*, 436−445.

(35) Guo, D.-S.; Chen, S.; Qian, H.; Zhang, H.-Q.; Liu, Y. Electrochemical stimulus-responsive supramolecular polymer based on sulfonatocalixarene and viologen dimers. *Chem. Commun.* **2010**, *46*, 2620−2622.

(36) Ma, X.; Sun, R.; Li, W.; Tian, H. Novel electrochemical and pH stimulus-responsive supramolecular polymer with disparate pseudorotaxanes as relevant unimers. *Polym. Chem.* **2011**, *2*, 1068−1070.

(37) Sun, R.; Xue, C.; Ma, X.; Gao, M.; Tian, H.; Li, Q. Light-driven linear helical supramolecular polymer formed by molecular-recognition-directed self-assembly of bis(p-sulfonatocalix[4]arene) and pseudorotaxane. *J. Am. Chem. Soc.* **2013**, *135*, 5990−5993.

(38) Guo, D.-S.; Zhang, T.-X.; Wang, Y.-X.; Liu, Y. Enzyme-responsive supramolecular polymers by complexation of bis(p-sulfonatocalixarenes) with suberyl dicholine-based pseudorotaxane. *Chem. Commun.* **2013**, *49*, 6779−6781.

(39) Zhu, L.; Lu, M.; Zhang, Q.; Qu, D.; Tian, H. Construction of polypseudorotaxane from low-molecular weight monomers via dual noncovalent interactions. *Macromolecules* **2011**, *44*, 4092−4097.

(40) Sun, R.; Zhang, Q.; Wang, Q.; Ma, X. Novel supramolecular CT polymer employing disparate pseudorotaxanes as relevant monomers. *Polymer* **2013**, *54*, 2506−2510.

(41) Ji, X.; Yao, Y.; Li, J.; Yan, X.; Huang, F. A supramolecular cross-linked conjugated polymer network for multiple fluorescent sensing. *J. Am. Chem. Soc.* **2013**, *135*, 74−77.

(42) Zhang, Q.; Yao, X.; Qu, D.-H.; Ma, X. Multistate self-assembled micro-morphology transitions controlled by host-guest interactions. *Chem. Commun.* **2014**, *50*, 1567−1569.

(43) Yan, X.; Xu, D.; Chi, X.; Chen, J.; Dong, S.; Ding, X.; Yu, Y.; Huang, F. A multiresponsive, shape-persistent, and elastic supramolecular polymer network gel constructed by orthogonal self-assembly. *Adv. Mater.* **2012**, *24*, 362−369.

(44) Zhang, M.; Xu, D.; Yan, X.; Chen, J.; Dong, S.; Zheng, B.; Huang, F. Self-healing supramolecular gels formed by crown ether based host−guest interactions. *Angew. Chem., Int. Ed.* **2012**, *51*, 7011−7015.