Cooperative organizations of small molecular surfactants and amphiphilic block copolymers: Roles of surfactants in the formation of binary co-assemblies

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Abstract
The construction of highly ordered organizations through self-assembly is one of the most popular phenomena both in natural and artificial environments. Amphiphilic molecules are the most commonly used building blocks for the self-assembly, which are conventionally known as amphiphilic low molecular weight surfactants with polar heads and nonpolar tails, or amphiphilic block copolymers (BCPs) consisting of covalently bonded hydrophilic and hydrophobic block chains. Compared with single surfactant self-assembly system, binary amphiphiles co-assembly systems composed of both small mass surfactants and amphiphilic BCPs feature high flexibilities and versatilities in materials designing and structure regulation, ascribing to the vast possibilities of intermolecular interactions within the systems and facile component modulations during the assembly processes. The amphiphilic features of the two kinds of molecules endow them with similar self-assembly behaviors, while the unique and distinct characters of each kind of amphiphiles lead to various complex systems and applications. Following this, the major potential applications of the nanomaterials synthesized from the binary amphiphiles in biological field are described. Finally, we shortly discuss the current challenges and future perspectives of the binary amphiphiles self-assembly systems.

KEYWORDS
amphiphilic molecules, binary self-assembly, block copolymer, mesoporous materials, surfactant

INTRODUCTION
Self-assembly is one of the most common and effective ways for constructing complex organizations in natural and artificial systems.1,2 In nature, various micro- and mesostructures have been fabricated from the spontaneous self-assembly of amphiphilic biomolecules, such as lipids and proteins, that are optimized to perform different biological functions.3,4 In artificial synthesis, self-assembly could occur among asymmetric amphiphilic molecules, resulting in well-organized and structure-defined supramolecular assemblies through noncovalent interactions.5,6 By rationally...
designing the molecular components and structures of the amphiphiles, unique self-assembled structures with various functionalities can be achieved. Amphiphilic molecules usually contain two components with significantly different or even opposite affinities to the solvents, for example, one component is highly affinitive to polar solvents while the other is more affinitive to nonpolar solvents. These molecules could be low molecular weight ones (conventionally known as surfactant) composing of the charged polar heads and nonpolar tails, or the amphiphilic block copolymers (BCPs) consisting of two or more distinct and immiscible block chains which are alternatively bound together through covalent bonds. Such distinctly differentiated affinities of the two ends of an amphiphilic molecule to a solvent may induce their spontaneous arrangement in this solvent based on the affinity effects to reach a minimized energy level of the system. Typically, in an aqueous solution, the hydrophobic weak interactions drive the association of the molecules, and the repulsive forces along with the steric effects between the polar heads give rise to diverse nanostructures and mesophases. These nanostructured supramolecular aggregates have been widely applied in the fields of biomedicine, food industry, cosmetic industry, painting, and coating, etc.

Comparing with the conventional self-assembled systems only using either single surfactant or BCP, the binary amphiphilic co-assembly systems combining both macro-molecular amphiphiles and small molecular surfactants provide a versatile platform for designing new functionalized materials. As the binary amphiphile system offers more adjustable parameters due to the combination of different amphiphilic molecules, the assembled structures obtained from the system can be comprehensively tuned through diverse types of inter-molecular interaction. These interactions could be the hydrophobic affinity between the hydrophobic parts of the two kinds of molecules, the charge interactions or hydrogen bonding within the hydrophilic heads, and the corporative effects in lowering the surface tension of the solvents. The similarity in the self-assembly behaviors of the two species makes them possible to co-assemble with each other into thermostable complexes. Meanwhile, the unique and distinct features of each kind of amphiphiles in, such as viscosity, crystallinity, and molecular sizes, enable their mutual interactions and the resultant micellar composites to present many varied forms. For example, the amphiphilic small molecule can be used as additive in modulating the aggregation of the polymers due to its small size and high mobility in solvent, or be used as emulsifier and stabilizer to adsorb at the interface of the polymer soluble/insoluble solution due to its higher affinity for both solvents. Thus, the cooperative self-assemblies of the dual-amphiphiles with well controlled hydrophilic/hydrophobic interactions would lead to enriched phase diagrams that cannot be achieved by individual systems. On the other hand, this versatility in the synthesis also provides us with more opportunities to design novel organic and/or hybrid materials with expected structures, dimensions, and functionalities.

In this review, we will focus on the binary or multiple amphiphiles systems cooperatively self-assembled from amphiphilic BCPs and surfactant molecules in different assembly patterns (Scheme 1). According to the roles played by the surfactants in the complex systems, we will present, 1) the co-micellization system where the surfactants and BCPs are simultaneously co-involved in the micellization process, and the surfactants act as assistants in the BCPs assembly; 2) the co-emulsification system where the surfactants work as emulsion stabilizer to assist the 3D confined assembly of BCPs within in emulsion droplets; 3) the co-templating system in which the aggregates of surfactants and BCPs reassemble into hierarchial structures, which are used as templates to guide the formation of hierarchical nanomaterials. After that, benefiting from the unique structures of the binary amphiphiles composites, potential applications in biomedicine fields of the obtained materials will be introduced. Finally, the challenges and perspectives in the further
researches of binary amphiphiles self-assembly systems will be shortly discussed.

SELF-ASSEMBLY THEORY OF SURFACTANTS AND AMPHIPHILIC BCPS

The self-assembly theory of surfactants

The self-assembly processes of small amphiphilic molecules, that is, surfactants, have been widely investigated for several decades. Depending on the charge types of the hydrophilic heads, surfactants have been categorized into: 1) Cationic type, which are mostly primary, secondary, tertiary amines, and quaternary ammonium salts, for example, octenidine dihydrochloride, cetyltrimethylammonium bromide (CTAB), cetyltrimethylammonium chloride (CTAC), etc; 2) anionic type, mainly including carboxylates, sulfates, sulfonates, and phosphates derivatives, for example, sodium dodecyl sulfate (SDS), sodium myristylcarboxylate (C14Na), sodium N-acyl-L-alanate (C14-L-AlaS); 3) zwitterionic type, which contains two opposite charges in one molecule, for example, dodecyldimethylamine oxide; 4) nonionic type, for example, octaethylene glycol monododecyl ether (C12E8), the commercialized Tween 80 (polyethylene sorbitol ester) and Span 80 (sorbitane monooleate), etc.

In aqueous solutions, surfactant molecules generate numerous kinds of aggregates at the concentrations higher than their critical micellar concentrations. This process is driven by the spontaneous efforts in lowering the energy level of the heterogeneous system, for example, in preventing the direct contacts between the hydrophobic chains and the surrounding water molecules. The structures of surfactant micelles can be approximately predicted by $g$ value depending on the following rules. At $g < 1/3$, spherical micelles are preferred, which may further assemble with each other into cubic or 3D hexagonal liquid crystals; while cylindrical micelles are formed in the range of $1/3 < g < 1/2$, which will lead to 2D hexagonal mesostructures; 3D cylindrical micelles will be produced at $1/2 < g < 2/3$; specifically at $g = 1$, the system will produce lamellar micelles; finally at $g > 1$, inverted micelles will appear (Figure 1). According to the equation, the morphology/shape of surfactant micelle in solution is determined by two important parameters, the cross-sectional area of the hydrophilic head and the length of the hydrophobic chains, which could be influenced by lots of factors such as molecular structure, concentration, temperature, ionic strength. Methods of tuning these factors will be considered as effective ways to regulate the self-assembly performance of the amphiphilic surfactants. Thus, these methods are widely applied in diverse micelle-related industry areas and provide strategies to regulate the highly ordered architectures in the formation of nanomaterials for uses in biomedicine, catalysis, and energy storages.

The self-assembly theory of amphiphilic BCPS

The amphiphilic BCPS exhibit self-assembly behavior similar to that of the small molecule surfactants. The microphase separation is induced by the incompatibility of different blocks in bulk state or in selective solvents, producing a large number of ordered aggregates. As the simplest BCP, the diblock copolymers $A$-$b$-$B$ have been extensively studied both in theory and experiment. The phase separation degree of $A$-$b$-$B$ melt is usually determined by the volume fractions of the $A$ ($f_A$) and $B$ ($f_B$) blocks, the total degree of polymerization ($N = N_A + N_B$) and the Flory-Huggins interaction parameter $\chi$, which evaluate the incompatibility of the $A$-$B$ blocks chains. Briefly, the degree of the microphase separation of $A$-$b$-$B$ could be speculated from $\chi N$ value ($\chi \times N$), which can be estimated by the Equation 2:

$$\chi N = \sum N \times V_{ref}(\delta_1 - \delta_2)^2 / RT,$$

where $V_{ref}$ is the segment reference volume, and $\delta_i$ is the Hildebrand solubility parameter for different polymer chains. From the equation, it can be inferred that the $\chi N$ value is a
function of temperature for a given molecule. Above a specific temperature, the phase of the BCPs will transfer from ordered to disordered one, and the temperature is called order to disorder transition (ODT) temperature, T_{ODT}.

The volume fraction $f$ is another important parameter. As shown in Figure 2A, the geometries of the polymers vary from cone, truncated cone to cylinder along with the increasing of $f_A$, which is similar to that of small molecular surfactants. According to the self-consistent field theory, under a fixed $\chi N$ value above the ODT ($\chi N > 10.5$), the increase of $f_A$ will lead to an order-to-order phase transition, which starts from closely packed body-centred cubic spheres to hexagonal cylinders, bicontinuous cubic phase, and finally to lamellar structures (Figure 2B).

Increasing the numbers of the chain blocks would greatly enhance the complexity of the self-assembly behavior of BCP due to the significant increasing of the interactions between the blocks. For ABC type triblock copolymers, more than 30 different types of morphologies have been theoretically predicted. Thus, the self-assembly behaviors of tri- or multi-block copolymers are far from clear, which need great efforts for further investigations.

The self-assembly behavior of BCP in solution is more diversified than in the bulk state due to the more complicated interactions under the existence of solvents. More than 20 kinds of diverse morphologies have been obtained for A-B-B diblock copolymers, including simple spherical micelles, cylinders or worm-like micelles, bicontinuous rods, bilayers in forms of lamellae structures and vesicles, hexagonally packed hollow hoop, and large compound micelles, etc. The morphologies of the thermodynamically stable BCP aggregates in solution could be controlled by three factors: the stretching degree of the core-forming blocks, the interfacial tension between the micelle core and the surrounding solvent, and the repulsive interactions among corona chains. These factors will be determined by a number of parameters such as the composition and the concentration of the polymer, the nature and mixed fraction of the mixture solvents, and the presence of the additives.

The most widely used amphiphilic BCPs are the polyethylene oxide-$b$-polypropylene oxide-$b$-polyethylene oxide (PEO-$b$-PPO-$b$-PEO) triblock series, which are well known as the trademark name of Pluronic from BASF company or Syneronic from ICI company. In aqueous solution, the respective hydrophilic and hydrophobic nature of the PEO and the PPO endow the copolymer with amphiphilic properties, forming large micellar aggregates in water. They have been vastly applied for diverse applications, such as drug loading, nanoparticle carrying, and synthesis of colloidal nanoparticles. Other amphiphilic BCPs could be ionic polymers with their hydrophilic parts composed of polyelectrolyte chains, including cationic BCPs such as pyridine-containing ones (e.g., PS-$b$-P4VP), amino-containing ones (e.g., poly(styrene-$b$-poly(2-(dimethylamino) ethylmethacrylate)) (PS-$b$-PDMAEMA) and anionic BCPs such as poly(acrylic acid) (PAA)-based ones (e.g. PS-$b$-PAA).

**Co-micellation of BCPs and surfactant**

According to the self-assembly theory mentioned above, the aggregation structures of BCPs are mainly determined by $g$ parameters, which is similar to that of small molecular surfactants. As discussed, ionic strength, which determines the interaction between the charged corona chains, will greatly influence the $g$ parameter of BCPs, and thus plays an important role in the micellar structure regulations. The ionic strength could be largely altered by the addition of trace amounts of ionic additives such as salts ions, acids, or bases. For example, the micellar structure of a kind of charged diblock copolymer, poly(ethylene oxide-$b$-styrene sulfonic acid) (PEE-$b$-PSSH), could be transferred from the spherical to rod-like and worm-like with the addition of small amount of NaCl, which is mainly due to the neutralization of the charge repulsive interactions among the charged PSSH segments.

Ionic surfactants are molecules containing both hydrophobic chains and ionic heads; therefore, adding a small amount of ionic surfactants as assistants is an effective ionic oriented
Surfactant co-micellization with nonionic BCP

Due to the high popularity of Pluronic series of polymers, studies have been intensively focused on the co-micellization of PEO-b-PPO-b-PEO triblock copolymers with surfactants. Almgren et al have firstly studied the interaction of PEO-b-PPO-b-PEO with anionic surfactant (e.g. SDS).\cite{31} The surfactant exhibited a significant promotion effect on the formation of polymer micelles, greatly lowering the critical micellization temperature compared to that of the pure polymers, which could be attributed to the “glue” effect of SDS on the hydrophobic PPO chains. The strong binding between the hydrophobic blocks and the tails of SDS confines the polymer micelles to form smaller particles than the pure polymeric micelles. However, too much SDS would burst the mixed micelles due to the increased intramolecular repulsions among the densely packed heads of the accumulatively adsorbed SDS, leading to the disintegration of the mixed micelles.\cite{40} Following this, the co-micellization of cationic and nonionic surfactants with nonionic BCPs has also been studies.\cite{41-43} The other two surfactants present similar effects with the anionic surfactants. The “glue” effect of ionic surfactants on the Pluronic triblock copolymer micelles is illustrated in Figure 3.

Surfactant co-micellization with ionic BCPs

In the case of co-assembly between surfactant and charged BCPs, the electronic interactions between the hydrophilic parts are another important factor that could determine the structures of the mixture micelles. Here, two possibilities need to be considered. In the first situation, the polyelectrolyte part of BCP and the surfactants have the same charge. Eisenberg et al have investigated the effects of anionic surfactant SDS on the micellar morphology of the negatively charged polymer PS-b-PAA.\cite{144} It was found that PAA blocks were partially ionized during micellization at near-neutral pH or above, so that the effective volume per corona chain was determined by the electronic repulsion between the ionized chains. SDS could influence the PS-b-PAA micelles in two different ways. One is the participation of the hydrophobic SDS chains into the core of the aggregate, and the other is the electrostatic screening effect from the sulfate and sodium ions on the partially charged PAA chains. These influences promote the architecture changes by altering the morphology of the aggregate initially in balance, resulting in a complicated phase diagram featuring morphology transitions from spherical to rod-like micelles and finally to vesicles along with the increasing SDS amount (Figure 4A). Comparing with the ionic salts additives, SDS provides additional possibilities for more diversified aggregate architectures and hence is a flexible and versatile micelle formation controller in the system.

In the second situation that the surfactant having the opposite charge to the ionic BCP, a stronger electrostatic interaction will occur, which is the main driving force for the morphogenetic transition of the mixture micelles.\cite{145} The structures of the composite micelles are a cooperative result of the electrostatic interaction of the charged blocks with the surfactants and the entropic interactions of hydrophobic blocks with the surfactant tails. For instance, Annaka et al have studied the co-assembly between polyelectrolyte BCPs poly(N-isopropylacrylamide)-b-poly (acrylic acid) (PNIPAm-b-PAA) and the oppositely charged dodecyltrimethylammonium bromide (DTAB).\cite{146} At a suitable charge ratio of surfactant to polymer, core-shell microstructure was formed. The densely packed DTAB+ micelles formed the core, hydrophobic PNIPAm chains formed the corona, and PAA worked as the connector between the core and corona. However, excess amount of DTAB would lead to the depositing of the micelles, due to the total charge neutralization. Using molecular dynamic simulations, a clear picture of the interaction has been obtained.\cite{47} As shown in Figure 4B, the composite of BCP/surfactant micelle adopted oblate sphere morphologies. The ionic surfactant micelle is composed of a densely packing core, and the charged block in the BCPs decorates the surfactant micelles to form an outer coronal layer, while the hydrophobic neutral block aggregates into a lamellar structure between the core and the corona, forming a core-shell morphology as seen from experimental results. Other aggregates, such as rod-like micelles, vesicular and worm-like micelles have also been obtained through regulation of the electronic interactions between the oppositely charged species.\cite{15,17}

Influences of co-micellization on the formation of mesoporous materials

The co-micellized binary amphiphiles could be used to template a series of nanomaterials, where the ionic surfactants could work as modulators. Zhao et al have studied the construction process of mesoporous materials templated by the co-micellization systems. During their investigation, small amounts of CTAB or SDS were added as structure modulators when the Pluronic series of triblock copolymer was used as template to synthesize mesoporous silica materials with large-sized mesopores.\cite{48,49} It was found that the interaction within the two amphiphiles was similar to that in the co-micellization process. For example, when SDS was added into the mesoporous synthesizing system using Pluronic P123...
Co-emulsification of BCP and surfactants

Regulating the structure, geometry and morphology of the colloidal polymer particles are of great significance in the self-assembly field. Inspired by the conventional emulsion polymerization method to polymerize uniform nanoparticles (PEO_{106-b-PPO}_{70-b-PEO}_{106}), SDS prefer to be absorbed on the hydrophobic PPO chains to increase the hydrophobic volume and lower the hydrophilic/hydrophobic volume ratio. Thus, the original hexagonal phase of P123 was transferred to bicontinuous cubic phase. Demicellization would happen at enhanced SDS concentration, similar to the pure co-micellization process. The effect of CTAB additive on the formation of nonionic polymer templated mesoporous silica was also investigated. Through increasing the amount of CTAB, the morphology of the resulting silica frameworks changed from hollow mesostructured sphere to worm-like structure and finally to ordered cubic mesophase, in consistence with the phase transition behavior of Fl27 micelles in the presence of additive surfactant CTAB (Figure 5). Thus, studies on the co-micellization system will facilitate a deeper understanding on the BCP/surfactant composite in other material systems.
in emulsion oil droplets, the confined self-assembly of BCPs in microemulsion, which is termed as co-emulsification process, represents a straightforward and controllable synthesis route for the preparation of uniformly self-assembled copolymer nanoparticles.\textsuperscript{[50]} Different from the co-micellization process, within the co-emulsification system, the small molecular surfactants are the emulsifier for the oil droplets. They are adsorbed at the oil/water interface to trigger the formation of uniform-sized oil droplets to confine the BCP assembly. The emulsification assisted by the surfactant is an important step of this confined assembly of polymers in the restricted 3D geometric space. Therefore, this co-emulsification approach of BCP and surfactants is another representative of the correlative interactions between polymers and the surfactants.

General approaches for the co-emulsification process

Briefly, the co-emulsification approach includes three steps: 1) dissolving the BCPs in an organic solvent (the oil phase); 2) emulsification of the oil phase in an immiscible solvent, such as water, to form dispersed oil droplets, which are stabilized by the amphiphilic surfactant; 3) evaporation of the organic solvent from the oil droplet to induce the self-assembly of BCPs (Figure 6A). The resulting morphology and structure of the polymeric nanoparticles could be governed by both thermodynamic parameters such as surfactant property,\textsuperscript{[52]} the geometry of the droplets,\textsuperscript{[53]} and the phase separation behavior of the copolymers,\textsuperscript{[54]} or the kinetic parameters such as the evaporation rate of the organic solvent.\textsuperscript{[51,55]}

Lu et al first put forward this combination concept based on the emulsification methodology and the phase separation of BCPs.\textsuperscript{[50,56]} The phase separation of amphiphilic copolymer poly(tert-butylacrylate)-b-poly(2-cinnamoyloxyethyl methacrylate) (PtBA-b-PCEMA) was confined in oil droplets, which were stabilized by emulsifier poly(2-cinnamoyloxyethyl methacrylate)-b-poly(glyceryl methacrylate) (PCEMA-b-PGMA). Afterwards, this method was extended to assemble numerous polymers in the presence of various surfactants. The polymer could be polystyrene-based amphiphilic BCPs like polystyrene-b-poly(4-vinylpyridine) (PS-b-P4VP),\textsuperscript{[57]} or PS-b-PEO,\textsuperscript{[58]} or ionic BCPs like poly(ethylene glycol)-b-poly(L-lactic acid) (PEG-b-PLA),\textsuperscript{[59]} The emulsifier could be cationic surfactant CTAB,\textsuperscript{[57]} anionic surfactant SDS,\textsuperscript{[60]} nonionic surfactant\textsuperscript{[61]} and even nanoparticles such as graphene quantum dots.\textsuperscript{[62]} With this, a rich variety of polymer particles with composite structures have been produced (Figure 6B), such as patchy nanoparticles,\textsuperscript{[57]} convex nanolenses with hexagonal distributed pores,\textsuperscript{[63]} lamellar nanoeilipsoids, and onion-like nanospheres,\textsuperscript{[64]} nanospheres with patterned surface,\textsuperscript{[65]} et al.

The roles of surfactants in the co-emulsification system

The amphiphilic surfactants play vital roles in the co-emulsification process, which is not only because of their emulsion stabilization capability, but also their preferential interaction with the BCP blocks. This kind of interaction will determine which block would be exposed to the outer surface of the droplet, then regulate the mesostructures at the interface of the emulsion droplets, finally influence the inner structure of the particles. For example, He et al have designed binary CTAB-derived surfactants to finely tune the self-assembly of a dendronized brush BCP in emulsion droplets (Figure 7).\textsuperscript{[66]} Each block of the BCP has
wedge-like side chains that could selectively bind with one of the CTAB-derived surfactant decorated with corresponding dendritic monomer units. This well-defined polymer/surfactant interaction allows the precise modulation of the interfacial properties of the assembled polymer particles, inducing their morphology transition from spheres to striped ellipsoids with featured alternating lamellas. The lamellar structure produces a near-perfect multilayer light reflection effect similar to 1D photonic crystals. Owing to its anisotropic architecture, the nanoparticles exhibit orientation-dependent light reflection which could be controlled by magnetic field after encapsulating magnetic nanoparticles. This unique light reflection effect has initiated a new class of on/off switchable magnetic activation coloration system.

The roles of BCPs in the co-emulsification system

The nature and composition of BCPs are other crucial parameters to determine the architecture, morphology, and the internal structure of the polymer particles. Based on the phase separation structures of BCPs in bulks mentioned in section 2.2, the typical phase-separated structures of the polymers are conventional body-centred cubic spheres, hexagonal cylindrical phase, bicontinuous cubic phase, or lamellar phase. However, the final unique morphologies of the co-emulsification particles are the results of the joint actions between the phase separation and a number of other extrinsic factors, such as polymer-surface interaction, the curved particle geometry, and interfacial affinity with the surfactant stabilizer. For example, coiled cylindrical particles could be derived from the original hexagonal cylinders phase; onion layered spheres could be obtained from the original lamellar phase. Designing special kinds of polymer molecules of distinct features could result in desired or unique morphological characteristics and properties. For instance, when the chiral segments were evolved in the polymer system, the obtained structures would present chiral structures such as helixes, coils, and twists. Li et al have examined the assembly behavior of chiral BCP polystyrene-b-poly(D-lactide) (PS-b-PDLA) within the 3D confined droplets stabilized by CTAB. Attributed to the chiral phase of PDLA, the particles exhibit spherical appearance with internal helical stripes and rough outer surface, or honey dipper-like elliposids.

It is worthy to note that the amphiphilic properties of the BCPs could also have a strong effect on the final morphology of the co-emulsification particles due to the interfacial instability. For the amphiphilic BCPs in an oil droplet, the strong interfacial affinity between the amphiphilic BCPs and the aqueous phase would drive the hydrophilic block to the oil/water interface. This phenomenon not only determines which block will be exposed to the surface thus influence the assembly structure, but also causes the interfacial instability due to the decreased interfacial tension, leading to unusual co-emulsification particles such as unstable emulsion droplets with porous structure, even collapse of the droplet into a series of small micellar structures, which has been firstly discovered by Zhu and Hayward et al.

In addition, instead of the typical conventional microphase separation, the amphiphilic BCPs within the oil droplet could experience micellization-rearrangement process by changing the oil phase from soluable to selective solvent. The micellization combined with co-emulsification will lead to special morphologies. For instance, Zhu et al has obtained porous nanocapsules or patchy polymer nanoparticles by combining the co-emulsification process with the micellization of PS-b-P4VP. In their works, PS-b-P4VP patch particles with distributed dots have been obtained using trans-1,2-dichloroethylene (PS-selective solvents) droplets, while the conventional pupa-like particles with lamellar structure...
have been formed using chloroform (non-selective solvents) droplets. The formation of the unusual patchy morphology was considered to be initialized by the formation of micelles of PS-\(b\)-P4VP in selective solvent in the oil phase. Along with the solvent evaporation, the rearrangement and condensation of the PS-\(b\)-P4VP micelles led to the formation of solid patchy particles.

Comparing with the diblock copolymers, the triblock copolymers present much more complicated assembly behaviors in the co-emulsification process. Xu et al have obtained geometrically asymmetrical copolymer particles using polystyrene-\(b\)-polysoprene-\(b\)-poly (2-vinypyrindine) (PS-\(b\)-PI-\(b\)-P2VP) asymmetric ABC triblock copolymers with coemulsifiers of CTAB and poly(vinyl alcohol) (PVA).\(^{[75]}\) When the size of the droplets was large enough, the morphologies could be transferred from onion-, bud to pupa, then to reverse bud and reverse onion by increasing the CTAB ratios. Special geometry such as Janus ring has also been obtained through another kind of ABC triblock terpolymers PS-\(b\)-PB-\(b\)-PMMA.\(^{[76]}\) The co-emulsification of PS-\(b\)-PB-\(b\)-PMMA with CTAB produced prolate lamellar ellipsoids with the PB microdomain being sandwiched between the lamellas of PS and PMMA blocks. Crosslinking of the PB block changed solid interlayer into Janus nanorings, while the disassociation of the PS and PMMA blocks resulted in the formation of strictly separated polymer brushes attached on the upper and lower sides of the rings. Thus, engineering the polymer composition will give polymeric nanomaterials with special geometries.

Formation of responsive polymeric colloids by co-emulsification

Sensitive responses to external stimuli are primary targets in designing smart materials. Based on the roles of the surfactant in determining the final structures, the responsiveness of the polymersomes formed in the emulsion method could be achieved through the rational engineering of the surfactant emulsifier. For example, by using light responsive surfactants containing light-active groups of the nitrobenzyl ester and coumarin ester as the emulsifier, Lee et al have successfully achieved light responsive colour/shape-changeable polymer nanoparticles (Figure 8).\(^{[77]}\) The tails of the surfactant could change from hydrophobic to hydrophilic after photo-cleavage under light irradiation (Figure 8A), resulting the variation of the exposure blocks on the polymer nanoparticle surface. As a result, the obtained particles transferred from onion-like spheres to oblate ellipsoids then to inverse onions in response to light irradiation (Figure 8B). Moreover, manipulation of the surfactant emulsifier would also produce thermo-responsive or pH-responsive nanoparticles. By combining CTAB with thermo-responsive poly(N-isopropylacrylamide) (PNIPAm) as a co-surfactant, Lee et al have developed BCP (PS-\(b\)-P4VP) particles that could reversibly change morphologies in response to temperature variations.\(^{[78]}\) At temperatures above the lower critical solution temperature (LCST) of PNIPAm chains, the PNIPAm chains would interact with P4VP in the chloroform droplet, meanwhile below the LCST, the chain preferred to migrate into the surrounding water phase. The movements of PNIPAm chains led to the changes in the volume fraction of P4VP within the assemblies, further influencing the shape and internal morphology of the BCP particles. Additionally, pH-triggered dynamic shape change could be realized by using functional binary surfactant mixtures (mixed CTAB and HO-CTAB) to regulate the phase separation of PS-\(b\)-P2VP followed by the cross-linking of the P2VP domains.\(^{[79]}\) The hydrophobic tails of CTAB were attracted to the PS domain, while the hydroxyl functionalized tails of HO-CTAB preferred to attach at the P2VP domain, forming ellipsoidal nanoparticles with surface-perpendicular lamellar structure. Since the side groups of pyridine could undergo protonation and deprotonation in response to pH, the cross-linking of the P2VP domain produced pH-responsive hydrogel discs interluding within the particles, which could change the particle morphology from ellipsoids to accordion-like particles by switching the pH value. Benefit from the reaction activity of pyridine groups, the pyridine type BCPs (such as PS-\(b\)-P4VP and PS-\(b\)-P2VP) could be used to produce more responsive systems.
For example, Zhu et al have obtained ion-responsive BCPs particles based on the coordination between the metal ions and four-vinyl pyridine units of PS-\textit{b}-P4VP.\textsuperscript{[80]} The obtained co-emulsification particles could experience structural transition by varying the type or the concentration of the metal ions, due to the shrinking of P4VP domains after coordination crosslinking.

Photonic crystals are highly ordered dielectric materials with periodically alternating refractive index.\textsuperscript{[81]} Especially, when the photonic crystals are endowed with stimulus-response properties, they will show potential applications in switcher, sensor, and security field. Zhu et al have constructed a solvent and pH-responsive BCP microspheres with concentric lamellar structure using ultrahigh molecular mass PS\textsubscript{133k}-\textit{b}-P2VP\textsubscript{132k} through a combined microfluidic technique and co-emulsification process.\textsuperscript{[82]} Upon swelling in ethanol or acidic solution, the periodic lamellas could expand to hundreds of nanometers which fits the photonic bandgap of visible light, generating solvent or pH responsive structure colors. Further, they constructed hollow photonic crystal microcapsule from PS-\textit{b}-P2VP copolymer in a water-in-oil-water double emulsion using ionic surfactant bis(2-ethylhexyl) sodium sulfosuccinate (AOT) and PVA as co-emulsifier (Figure 9).\textsuperscript{[83]} The microcapsule could reflect visible light exclusively due to the concentric lamellae in the shell. Compared with the former solid microspheres of PS-\textit{b}-P2VP, these microcapsules exhibit bright structural colors with better monochromaticity. The pH-responsive swelling of the P2VP domains also endowed the microcapsules with pH responsive structure colors, as shown in Figure 9C.

Co-templating of BCPs and surfactants into inorganic frameworks

Since Mobil company announced the first ordered mesoporous silicas (MCM series), great efforts have been devoted to exploring the mesoporous materials templated from amphiphilic assemblies.\textsuperscript{[8,84–86]} These amphiphiles could be ionic surfactants (e.g. alkyl quaternary ammonium salts, alkyl sulfate/amino acids),\textsuperscript{[87,88]} polymers (nonionic amphiphilic BCPs of Pluronic F127 and P123, ionic BCPs of PS-\textit{b}-PAA and PS-\textit{b}-PVP),\textsuperscript{[89–91]} and biomacromolecules (peptide, DNA, etc.).\textsuperscript{[92]} The co-assembly of the inorganic sources and the amphiphiles would form rigid inorganic frameworks surrounding the ordered structures. After removing the templates, inorganic nanomaterials with uniformly arranged mesopores were thus obtained. According to the design principle, single template usually produces porous materials with mono-sized pore structure. However, requirements on the formation of hierarchically mesoporous materials have risen due to their potential applications in energy storage, catalysis, analytics, and life science.\textsuperscript{[86,93,94]} A strategy called “dual-templating method” has been developed to create hierarchically mesoporous materials by choosing binary surfactants containing both amphiphilic BCPs and small molecular surfactants as co-templates.\textsuperscript{[95]} Attributed to the size and geometry difference of the two individual micelles, mesoporous materials templated from the binary amphiphiles may contain dual sets of pores with differentiated pore sizes and channel arrangements. However, since the two template molecules prefer to form separated phases or mixed micelles through the co-micellization from the thermodynamic point of view, establishing suitable interactions between the two micelles become considerably important in constructing a co-templating system.

Ionic BCP with ionic surfactant

The co-templating method was firstly conducted by the binary amphiphiles containing electrostatically bound amphiphilic polymers (the anionic PS-\textit{b}-PAA) and surfactant (the cationic CTAB), where silica source was used as inorganic source to replicate the hierarchically arranged micelles.\textsuperscript{[95]} Our group has developed a series of dual-modal mesoporous silica nanoparticles based on this co-templating system (Figure 10A).\textsuperscript{[95–98]} During the co-templating process, the bridging effect of CTAB is important since single PS-\textit{b}-PAA lacks sufficient interaction with the backbone species, the hydrolyzed silane. In slightly basic aqueous solution, the hydrophilic PAA blocks could couple...
with CTAB micelles via electrostatic Coulomb force to form the CTAB-coated micelle or composite micelles. Then CTA$^+$ groups on the composite micelle bind with the added silica source, resulting in the formation of ordered inorganic-organic hybrid aggregates following the hydrolysis of the silica source. The obtained dual-mesoporous silica spheres exhibit a core-shell structure, composed of small pores (2.0 nm) in the shell templated by CTAB micelles and larger pores (12.8–18.5 nm) in the core templated by PS-b-PAA micelles. An important feature of the binary surfactant system is their high flexibility in tuning the microphase separation of the BCPs, providing a feasible way to control the large channel structures of templated silica materials. Thus, just varying the addition amount of CTAB could produce a series of mesostructured silica nanoparticles including hexagonal, cubic, and lamellar arranged large pores, showing potential capabilities in capsulizing various kinds of guests. In addition, the distribution of the small pores in the dual mesoporous materials was controllable. By changing CTAB concentrations, the position of the small pores could move from the shell into the inner framework of the large pores (Figure 10B).

**Nonionic BCP with ionic surfactant binary system**

The co-templating strategies were further demonstrated by combining the nonionic polymers and ionic surfactants. In order to overcome the complete segregation or coalescence of the nonionic polymeric micelles and ionic surfactant micelles, Zhao et al put forward an evaporation-induced aggregating assembly (EIAA) method for the efficient co-assembly of BCP and surfactant micelles. This method starts from the pre-aggregation of the polymer through the micro phase separation during the solvent evaporation and then incorporation of the mature surfactant micelles. The pre-assembled aggregates of the polymer could be treated as a hard template, which will be less-influenced by the incorporation of extra smaller amphiphilic surfactants. During this, both copolymers and surfactant micelles are considered as structure directing agents for inorganic sources to construct hierarchically porous structures. Based on this principle, Zhao et al obtained dual-mesoporous silica templated from the BCPs micelles. At elevated concentrations, the strong interaction between CTAB and PAA chains leads to a homogenized distribution of CTAB micelles within the PAA coronas. The feasibility of the binary templating system in controlling the mesostructures, pore sizes, and distributions in the hierarchically porous materials have greatly enriched their applicability in nanomedicine or catalysis.
materials from the co-templates containing PEO-$b$-PMMA and smaller amphiphilic surfactant alkyltrimethylammonium bromide (C$_n$TAB) (Figure 11A).\textsuperscript{100} The large mesopores (around 20 nm) and the small worm-like mesopores (around 2.5 nm) were templated from the BCPs micelles and the amphiphilic surfactant assemblies, respectively, and the small pores distributed homogeneously in the silica wall of large pores. By introducing Au nanoparticles into the large pores, those specially pore-distributed materials exhibit high catalytic performance for the epoxidation of styrene.

More than appearing-like conventional powders, the hierarchical materials constructed through the binary templating methods could be extended into different dimensions such as 2D freestanding sheets or defined 0D nanospheres. Liu et al have reported the fabrication of a 2D conducting polymer nanosheet with mesoporous surfaces through synergically manipulating the co-assembly between the 2D bilayer assemblies of amphiphatic perfluorinated carboxylic acids (PFCA) and the spherical micelles of PS-$b$-PEO (Figure 11B).\textsuperscript{101} The two assemblies were preassembled in solution separately and then co-assembled into hierarchical superstructures upon simply mixing. The spherical PS-$b$-PEO micelles spontaneously packed on both interfaces of the free-standing lipid PFCA bilayers to form the hierarchical supramolecular assemblies, driven by the hydrogen bonding interaction between the PEO coronae and the carboxylic group of PFCA. The obtained 2D hierarchical materials further worked as template to confine the polymerization of aniline monomers to form the meso-scaled conductor polymers polyaniline sheets, which display anisotropic and record-high electrical conductivity for potential uses in flexible electronics. Furthermore, another kind of 2D mesoporous sheet composed of polypyrrole was obtained by employing amphiphilic aliphatic amine octadecylamine instead of PFCA.\textsuperscript{102} The nanosheets showed superior electrochemical performance in Na-ion batteries.

In the soft-templating method, single micelles are the smallest units in the formation of ordered mesoporous nano-materials, nanospheres, and nanorods.\textsuperscript{103} Thus, the hierarchically hollow mesoporous nanoparticles could be obtained from the co-assembly between the single micelles of BCP and the assembled micellar aggregates of amphiphilic surfactant. Yamauchi et al designed a dual-template route composed of nonionic triblock polymer polystyrene-$b$-poly(2-vinyl...
pyridine)-b-poly(ethylene oxide) (PS-b-P2VP-b-PEO) and cationic surfactant CTAB to synthesize hollow mesoporous silica nanoparticles.\[^{104}\] In a basic solution, the P2VP blocks interacted with the negatively charged hydroxylated silicate through hydrogen bonding, and the positively charged CTAT+ micelles were attracted onto the surface of the polymer micelles. As a result, the single polymer micelles served as templates to form hollow silica nanoparticles with an inner cavity of around 17 nm in diameter, while CTAB contributes to the formation of the mesoporous shell surrounding the cavity. During these processes, the silica source of TEOS was also the connectors between the dual templates.

In addition, the combination of soft binary amphiphiles templates with hard templates would induce enhanced complexity in the porous dimensions, possibly resulting in tri-modal porous silica materials. These hard templates could be the hard colloids such as inorganic nanoparticles, polymeric nanospheres, or rigid supramolecular aggregates. For instance, using hard templates PS latex sphere and the binary soft templates of diblock copolymer poly (ethylene-co-butylene)-b-poly (ethylene oxide) (KIE) and ionic liquid surfactant [H(CH2CH2)0.67(CH2(CH)CH2CH3)0.33]100 (OCH2CH2)60OH], Kuang et al have obtained silica materials simultaneously possessing tri-modal porous structures.\[^{105}\]

The ultra-large pores of 360 nm in diameter are clearly from the uniform PS latex spheres stacking. Meanwhile, polymer KIE and the ionic liquids acted as the templates for the larger mesopores of about 12 nm and smaller mesoporous of around 2 nm in sizes, respectively.

### Modified Stöber method

The co-templating route can be developed as a modified Stöber approach that could efficiently produce ultra-small mesoporous silica nanoparticle. In this aspect, ammonia-catalyzed growth could take place through surface reaction-limited condensation, and mesoporous silica nanoparticles could be synthesized using binary surfactants with one as the template and the other as capping agent.\[^{106}\] For example, Imai et al have synthesized a kind of hexagonal mesoporous silica nanoparticle using the binary surfactant system containing cationic surfactant CTAC and Pluronic F127 (Figure 12A).\[^{107,108}\]

Different from the single-micelle templating route mentioned in 3.3.2, the mesoporous structure was mainly templated by small CTAC micelles, while F127 played a role of capping agent. During the synthesis, F127 surface-anchored on the CTAC micelle-silicate nanoparticles to inhibit the continuous growth of the individual particles, confining the mesoporous nanoparticle sizes within only tens of nanometers. In addition, using this copolymer-involved modified Stöber method, other ultrathin mesoporous silicas with different structures such as cubic Ia-3d (MCM-48 type)\[^{109}\] and helical mesostructures\[^{110}\] have been developed by tuning the amounts of the binary amphiphilic surfactants or changing the reaction conditions.

The surface-anchored copolymers could further work as templates to form hierarchical mesostructures. Yeh et al have prepared hollow silica spheres equipped with mesoporous shells by using a ternary surfactants system. The CTAB, SDS was chosen as the templates, and Pluronic P123 was used as the reaction-terminating agent (Figure 12B).\[^{111}\]

The inner hollow cavity was templated by the bilayer vesicle formed from CTAB-SDS binary surfactants. Then, P123 surface-anchored on the CTA-SDS vesicle and formed the mesoporous silica shell through a fast silicification step. By tuning the surfactant and copolymer composition, the obtained hollow mesostructured silicas showed varied diameters, pore sizes, and structures. Moreover, by different inorganic/organic precursors, this method can be extended to prepare diverse kinds of hollow materials, such as hollow mesoporous carbon materials\[^{112}\] and carbon spheres.\[^{113}\]

Furthermore, when the vesicles were encapsulated within pre-prepared core materials, this vesicle-templating strategy was used to produce various kinds of yolk-shell materials equipped with mesostructured shell and different types of cores (e.g. silica spheres, gold particles, or magnetic nanoparticles).\[^{114}\]

The roles of BCP and the surfactant could interchange in the modified Stöber method, that is, the surfactant could be employed as steric stabilizer while the polymer worked as mesoporous template. The formation of IBN-series silica materials was fabricated based on this strategy. Using Pluronic series copolymers (F127, F108, P65, P123) as templates and highly hydrophobic surfactant, the cationic fluorocarbon surfactant [C2F5O(CF3CFCF3O)2CFCF3 CONH(CH2)2N+(C2H5)2(CH3)1] (FC-4) as a capping agent, Han and Ying have obtained a series of silica materials (IBN-1 to IBN-5) with large-porous structures featuring cubic, mesocellular and 2D hexagonal and disordered pore channels.\[^{115}\] The periodically mesostructured particles were templated by the supramolecular assemblies of the triblock copolymer and terminated by the capping of FC-4. The high surface activity of FC-4 and the immiscibility between the copolymer and FC-4 enabled FC-4 to be adsorbed at the particle periphery to limit the growth of particles. Moreover, the fluorocarbon surfactant would further orderly pack around the mesoporous silica particle to form a mesoporous shell, resulting in mono-shell or multi-shelled mesoporous silica spheres.\[^{116,117}\]

More than an efficient way to construct hierarchical materials, the co-templating method which solidifies the soft matters into hard framework also provides a strategy to directly observe the co-assembly process among the multi-amphiphiles and study the interaction mechanisms between the binary micelles, which will further promote the development of soft matter.

### BIOLOGICAL APPLICATIONS OF THE NANOMATERIALS CONSTRUCTED FROM THE BINARY AMPHIPHILE SELF-ASSEMBLY

Along with the development of nanotechnology, nanomaterials have demonstrated high potentials in the biological field. Nanomaterials constructed from the amphiphile self-assembly have already been applied as nanomedicines, nanosensors, and tissue rebuilders, etc., in both therapy and diagnosis. In order to meet the requirement of modern biology, the nano-biomaterials for biological applications such as cancer diagnose, targeted cancer therapy, tissue engineering need to be highly feasible, intelligent but easy to modulate. With the advantages of the binary amphiphile self-assembly
FIGURE 12  a1). Schematic representation of the synthesis of ultra-small mesoporous silica nanoparticles from the binary surfactants containing CTAC and F127. a2). TEM images of the mesoporous silica particles prepared with 4.9 mM F127 ([TEOS] = 0.52 M, [CTAC] = 0.25 M, [NH₄OH] = 1.54 M, reaction time 1 h, pH = 2). Reproduced with permission: Copyright 2006, American Chemical Society. b1) Schematic diagram of the formation of hollow mesoporous silica spheres from the co-assembly of CTAB, SDS, and P123. b2) TEM images of the hollow silica spheres. Reproduced with permission: Copyright 2006, American Chemical Society

system, the produced biomaterials are endowed with large diversities in regulating the structures and morphologies, which are beneficial for the designing of smart biomaterials with desired versatility, designability, and intelligence. Especially, the design of novel binary amphiphile biomaterials could rely on the existing amphiphiles that avoid the synthesis of new polymers or other building blocks, which will greatly expand the practical potentials of biomaterials. The featured applications of the biomaterials obtained from above three different strategies of the binary amphiphile self-assembly are discussed in this section.

Applications of the biomaterials from the co-micellization system

Drug cargos

The loading of guest drug molecules in polymeric micelles has been studied for a long time period. Considering great advantages of the co-micellization method in regulating the structures and functionalities of the polymeric micelles, controlled drug loading and releasing via structure transition could be achieved through reasonably designing the BCP and surfactant additives. Hu et al designed a kind of composite micelle containing PS-b-P4VP and additive surfactant perfluorooctanoic acid, which could undergo a sphere-to-vesicle transition in response to the increasing amount of solvent. During such a sphere to vesicle transition, the composite micelles could swallow large amount of guests dispersed in surrounding solvent, leading to the maximized loading capacity that cannot be achieved in the spherical state, which will be used in drug loading and delivery.

Tissue engineering

The polymer scaffolds are powerful tools of tissue engineering in mimicking the biological environment and controlling the growth of new tissues. The surface topographical nanopatterns which can be formed by the substrate self-assembly of BCPs have shown great potentials in mimicking the nature extracellular matrices. As a highly tunable system in structure variations, the binary surfactant system
has advantages in tuning the structure by simple combining BCPs with appropriate surfactants without the need of synthesizing new polymers. Lee et al designed a series of polymer surface nano-structures such as nanospots or nanodomains by the corporative self-assembly of PS-b-PEO with ionic surfactant dodecylbenzenesulfonic acid. The surfactant was used to control the microphase separation behavior of the copolymer on substrate, resulting in the changes in the PS domain sizes. These regulations on the copolymer surface patterns greatly influence the cell adhesion, proliferation, and differentiation of the osteoblastic cells planted on the substrate.

Applications of the biomedicines from the co-emulsification system

The efficient and selective delivery of medicine upon external stimulation is a critically important property for nanocarriers in biomedical field. In the co-emulsification approach, the structures and morphologies of the obtained polymersomes are controllable and changeable in response to various simulations, as mentioned in 3.2.4. The properties such as solvent-, thermo-, and photothermal responsiveness make it possible to design multifarious stimulus responsive guest molecular carriers through the co-emulsification strategy, presenting great potentials in smart therapy.

Structure-controlled drug release

Since the binary amphiphile systems are highly flexible and feasible in controlling the final structures of the obtained materials, these systems provide excellent platforms featuring structure transition and morphology-dependent drug release behaviors. Zhu et al have investigated the structure-dependent drug-releasing behaviors by designing drug-loading capsules of varied porous structures through the co-emulsification method (Figure 13A). Three types of capsules with spherical, cylindrical, or lamellar mesoporous shells were prepared from the self-assembly of PS-b-P4VP. The drug releasing behaviors and the corresponding cell apoptosis efficiencies were evaluated by loading rhodamine 6G and doxorubicin (DOX) in the capsules. The sphericalshelled capsules exhibited the fastest drug release and highest apoptosis ratio while the lamellar ones showed the slowest but stepwise release. Moreover, the releasing rates from the capsules could be greatly enhanced by decreasing pH value from 7.0 to 4.0, due to the deprotonation of P4VP under elevated pH value. The programmable release behaviors by simply engineering the shell structures could meet the requirements of different applications such as burst or controlled release.

Stimuli-responsive drug release

A variety of stimuli-responsive BCPs nanoparticles have been obtained by rational-designing the compositions of the BCPs and/or the emulsifying surfactant, which opens more possibilities for smart nanomedicines. As described, the deprotonation of P4VP chains under basic conditions would endow P4VP with stimulation responsiveness property. Thus, a series of pH-responsive guest molecular carriers have been designed based on the BCPs-containing P4VP blocks. Ku et al has developed a simple method for the formation of pH-responsive porous nanoparticles using PS-b-P4VP and SDS. Nanoparticles of non-porosity, closed-porosity, and open-porosity have been obtained depending on the concentration of SDS. Attributed to the pH-sensitive electrostatic interaction between the water-soluble guests and the pH-sensitive P4VP pores surface, these porous nanoparticles could be used as pH-responsive drug nanocarriers. Furthermore, nanoparticles constructed from the BCPs of PNIPAm-containing PNIPAm-b-PLGA or PS-b-PNIPAm-b-PS have been used for the thermo-responsive drug delivery and diagnosis, due to the low cloud point temperature (around 32°C) of PNIPAm chains, which is close to the body temperature.

The redox-responsive nanomedicine is another strategy for designing smart cancer therapy method. Staff et al prepared redox-responsive patchy nanoparticles using poly(phenylferrocene-b-poly(methyl methacrylate) (PVFc-b-PMMA) as the building block and SDS as emulsifier. The PVFc blocks formed the patchy domains within the nanoparticles that could transit from hydrophobic to hydrophilic upon oxidation. This transition of the patchy domains resulted in the swelling of the PVFc toward the surrounding water, leaving large channels that could allow the release of hydrophobic payloads in response to the oxides (Figure 13B). These examples provide strategies in further designing smart anticancer nanomedicines.

Applications of the hierarchical materials by the co-templating method

Drug delivery

The hierarchically porous materials provide a platform for loading various kinds of guest species. Compared with the single porous material, the hierarchical porous structures enable the high-capacity loading for a variety of guest species including small molecules, macromolecules, and even functional nanomatters/nanoparticles, making them widely applicable in drug delivery, diagnosis, and pollutant purification. Our group has investigated the loading capacities of the dual mesoporous silica nanospheres for multi drugs such as hydrophobic drugs, anti-tumor drug and gene. Benefitted from the different properties of the dual templates, the hierarchical pores could be programmatically modified with different functional groups, which endows them with co-loading ability for both hydrophobic and hydrophilic medicines. Thus, the therapeutic effect was improved compared with their single drug loading counterparts (Figure 14). Moreover, the efficiencies of cell adhesive interaction and cell endocytosis by the drug-loaded nanomaterials are the key points affecting the therapeutic and imaging outcomes of the nanomedicines. The facile tunability of the binary self-assemble system on morphology regulation provides a superior model for investigating the cellular uptake behaviors. Therefore, it is easy to investigate the shape dependence of dual-mesoporous silicas on the cell endocytosis efficiency. These silica nanoparticles were
FIGURE 13  (A) Structure-dependent drug release from capsules of different mesoporous structures assembled form PS-\textit{b}-P4VP with PVA. a1-a6) TEM images and the illustration of the nanocapsules with spherical (S) (a1,a2), cylindrical (C) (a3,a4), lamellar (L) (a5,a6) mesopores. a7) Drug release profiles of R6G from the capsules at different pH and a8) the corresponding cell apoptosis induced by the DOX-loading capsules with different mesopore structures.[73] Reproduced with permission: Copyright 2016, Wiley-VCH. (B) The redox-responsive drug releasing nanomedicines using PVFc-b-PMMA as the building block and SDS as emulsifier. b1) Preparation schematics of the nanomedicine. b2,b3) Illustrations of the redox-responsive mechanisms of the PVFc block chains b2) and the nanoparticles b3). b4) The release kinetics of pyrene from the PVFc-b-PMMA patchy nanoparticles in response to the oxidation triggering.[127] Reproduced with permission: Copyright 2012, American Chemical Society

obtained by the binary surfactant templating method, through silica-replicating the co-assembles of charge-complementary PS-\textit{b}-PAA and cationic type low-molecular weight surfactants. Various kinds of morphologies including pupa-like ellipsoidal, onion-like spherical and hexagonal spherical mesoporous silica nanoparticles have been obtained by regulating the alkyl chain lengths and the polar heads of the ionic surfactants. The morphology of the mesoporous silica nanoparticles influences the cellular uptake of SMMC-7721 cell line. The ellipsoids have higher cellular uptake efficiency than their spherical counterparts, which is inspirable for the further design of drug nano-cargos.

Bioimaging

The bioimaging is an effective tool in disease (such as cancer) diagnose and disease adjuvant therapy. Various kinds of sophisticated bioimaging approaches including fluorescence, X-ray computed tomography, magnetic resonance and positron emission tomography, have been developed nowadays. Owing to the dual mesoporous structure and the unique loading capacity, hierarchically porous materials are also suitable for the bioimaging applications. The gold nanorods with localized surface plasmon resonance within the near-infrared wavelength range could be used in bioimaging.
FIGURE 14  Programmable modification of the dual-mesoporous materials for the co-loading of the hydrophobic and hydrophilic drugs. (A) Schematic representation of the programmable modification. (B) Drug release profile of the hydrophobic drug curcumin (Cur) and the hydrophilic drug DOX. (C) Comparison of the viabilities SMMC-721 cells after incubation with the non-l, single and dual drug loaded mesoporous materials.[97] Reproduced with permission: Copyright 2017, American Chemical Society

FIGURE 15 (A) Illustration of the preparation of dual mode magnetic resonance nanoparticles by loading manganese species within the pore structure of dual-mesoporous silica spheres through the in situ calcination and reduction of KMnO₄. (B) In vivo T1- and T2-weighted magnetic resonance images, and (C) the corresponding signal intensity of a rat liver after the injection of the nanoparticles.[134] Reproduced with permission: Copyright 2013, American Chemical Society

applications, including light optical scattering,[130] optical coherent tomography,[131] and photothermal therapy.[132] Ascribed to the spatial confinement by the special pore structure, the dual mesoporous silica materials have been used for the bioimaging by loading with gold nanoparticles,[133] gold nanorods,[128] showing enhanced in vivo CT imaging capability and NIR adsorption photothermal effects compared with gold nanorods alone, while maintaining low body toxicity and body fluid stability.

As one of the modern diagnose technologies, magnetic resonance imaging (MRI) features non-invasive safety, fast, and vivid spatial imaging capability. Niu et al designed a manganese-based dual-mode contrast agent for both T1- and T2- weighted MR images by loading manganese oxide in the dual mesoporous silica materials.[134] The loading of the ultrasmall manganese oxide was achieved through in situ oxidation and reduction of the manganese source KMnO₄ within the pores. The Mn-based silica nanospheres displayed an extraordinarily high T1 relaxivity (r1) of 10.1 mM⁻¹s⁻¹ and a moderately high T2 relaxivity (r2) of 169.7 mM⁻¹s⁻¹, producing excellent simultaneous dual-mode MRI (Figure 15).
CONCLUSION AND PERSPECTIVE

In conclusion, we have summarized the binary self-assembly systems constructed from the cooperative interactions between amphiphilic BCPs and the surfactant molecules for the syntheses of organic-inorganic nano-hybrids and mesoporous-structured nano-materials. According to the roles of the small molecular surfactants in the binary systems, three different modes of the binary amphiphile systems have been introduced. Various fascinating nanostructured materials of unique characteristics and diverse application potentials have been synthesized from the binary self-assembly systems, which exhibits the bright prospects of this field.

Despite the great progresses that have been made in the past decade, considerable challenges still remain in the binary amphiphile systems. From the material design point of view, the chemical and physical properties of the amphiphilic molecules are the fundamental determining factors for the success of the aggregate synthesis of desired structures and properties. However, up to date, most of the BCPs employed in the binary systems are limited to the simplest linear diblock copolymers, whose phase separation has been extensively investigated. The diversity of the synthesis and the final structure of the assembled nanomaterials mostly fall in the well-understood spherical, cylindrical, bicontinuous, and lamellar phases. Extending the BCP types or varying the combination forms between the blocks will greatly enlarge the combination probabilities between different blocks and thus provide large spaces for the parameter regulations in the assembly, producing a much enriched diversity of the self-assembled nanostructures and materials. Although theoretic simulations on the assembly of more complex BCPs such as ABC linear or symmetric ABC star triblock terpolymer in confined spaces have been reported,[135,136] which provided an unprecedented guiding theory for the BCPs self-assembly, the experimental behavior of these BCPs are still not fully understood. Furthermore, in addition to the linear copolymers, other asymmetrically branched copolymers like brush-like polymers, dendritic polymers, star-like copolymers and alternating copolymers are also good candidates expectedly for more complex phases.

The real mechanism of the self-assembly behavior and formation kinetics of these materials are still in the mist. The precise description of the formation process remains a challenge due to the extremely complex interactions among the vast number of components that are involved in the synthesis system. So far, the reported mechanistic speculations have been mostly based on the final and macroscopic experimental results, lacking direct evidence on the molecular and atomic level in real-time. Fortunately, this challenge could be hopefully solved along with the developments of the sophisticated characterization tools, especially the soft matter image and in situ techniques. For instance, the resolutions of the recent spherical aberration corrected and cryo-transmission electronic microscopy have been elevated down to the atomic scale,[137] and femtosecond time-resolved chemical kinetics and phase transition observation have been applied to reveal the ultrafast reaction procedure,[138,139] enabling us to observe the detailed reaction process from the single molecular level. Moreover, computer simulation on kinetics of the self-assembly will be another key approach to understand the detailed process. The optimization of arithmetic and the improvement in the super computer or quantum computers will make molecular dynamic simulations a powerful and accessible technique for solving more complex systems. The combination of these technique tools and simulations may provide us high probabilities to acquire new understanding into the mechanisms on the assembly behavior of the current and the future soft matter systems.

Although there are numbers of problems remaining in this area, the fast developments in solving the multi-body system problems will create ever-larger possibilities enabling us to study the binary amphiphilic self-assembly topics. The in-depth understanding of the self-assembly synthesis and underlying mechanism probing along with the property modulation and application exploration in this filed will greatly enrich the soft matter science and benefit the nanomaterial industry. We believe the present short summary on the binary self-assembly could be helpful for the research in chemistry and material science in further developing novel materials of unique properties for the potential applications in diversified fields such as biomedicines, energy technologies, and electrooptical devices.

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REFERENCES

1. D. N. Reinhoudt, Supramolecular Materials and Technologies, Wiley, Chichester 1999.
2. Z. Liu, J. Qiao, Z. Niu, Q. Wang, Chem. Soc. Rev. 2012, 41, 6178.
3. D. Lombardo, M. A. Kiselev, S. Magazù, P. Calandra, Adv. Cond. Matter Phys. 2015, 2015, 151683.
4. B. J. G. E. Pieters, M. B. van Eldijk, R. J. M. Nolte, J. Mecinović, Chem. Soc. Rev. 2016, 45, 24.
5. T. Aida, E. W. Meijer, S. I. Stupp, Science 2012, 335, 813.
6. A. Sorrenti, O. Illa, R. M. Ortuño, Chem. Soc. Rev. 2013, 42, 8200.
7. T. Christoff-Tempesta, Y. Cho, D.-Y. Kim, M. Geri, G. Lamour, A. J. Lew, X. Zuo, W. R. Lindemann, J. H. Ortony, Nat. Nano. 2021, https://doi.org/10.1038/s41565-020-00840-w.
8. Y. Wan, D. Zhao, Chem. Rev. 2007, 107, 2821.
9. Y. Mai, A. Eisenberg, Chem. Soc. Rev. 2012, 41, 5969.
10. C. Tanford, The Hydrophobic Effect: Formation of Micelles and Biological Membranes, John Wiley & Sons, New York 1973.
11. J. H. Finkelthop, W. Helfrich, Chem. Rev. 1993, 93, 1565.
12. W. Yasen, R. Dong, A. Aini, X. Zhu, J. Mater. Chem. B 2020, 8, 8219.
13. P. Müller-Buschbaum, M. Thelakkat, T. F. Fässler, M. Stutzmann, Adv. Energy Mater. 2017, 7, 1700248.
14. Z. Hu, W. Verheijen, J. Hoffens, A. M. Jonas, J.-F. Gohy, Langmuir 2007, 23, 116.
15. J. F. Berret, Adv. Colloid Interface. 2011, 167, 38.
16. S. Papas, Soft Matter 2011, 7, 8697.
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