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PAPER

Multicompartment and multigeometry nanoparticle assembly†

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The directed or dynamic assembly of molecular components in solution is a simple and effective strategy to confine materials in desired geometries and length scales. We use a kinetic control strategy with block copolymer blending to construct complex nanoparticles through the demixing of unlike block copolymers within the same nanoscale particle. Successful nanoparticle construction relies on kinetic trapping of unlike block copolymers into the same nanoparticle with solution processing. Not only can we make nanoparticles with multiple internal compartments of a desired size, but we can also make nanoparticles of hybrid geometries (*e.g.* a blend of cylindrical and spherical geometries). These combination particles are kinetically trapped, non-equilibrium structures. However, the block copolymers are able to phase separate locally within the nanoscale particle, thus producing internal compartments and hybrid geometries.

Small molecule lipid and surfactant amphiphiles are well known to form nanostructures in aqueous solution, such as spherical micelles, cylindrical or worm-like micelles, or bilayer vesicles.¹ Mixtures of small molecule amphiphiles can be formulated to produce effects like the formation of specific, spontaneous vesicle sizes² or to stabilize network phases of cylindrical micelles with trifunctional branch points.³ These small molecule amphiphile mixtures are predominately equilibrium structures because of frequent molecular exchange between the aggregated state and the unimer state in solution. If one does not rely on equilibrium but instead uses kinetic processing for molecule assembly and nanoparticle construction, an entirely new realm of nanoscale complexity is possible. Processes such as nanoscale molding,⁴ flash nanoprecipitation,⁵ nanoemulsification,⁶ and solvent processing⁷ are all excellent examples of new control provided over nanoscale structure. We have developed a simple solution blending strategy that provides kinetic control of unlike block copolymer assembly to produce multicompartment and multigeometry nanostructures. First, we can force unlike block copolymers into a nanoparticle with a single geometry (*e.g.* a sphere). After confinement within the sphere, the unlike

polymer block components within the cores demix into distinct internal compartments of desired size corresponding to the amount of each unlike block copolymer present through simple blending. Second, we can force unlike block copolymers into a nanoparticle and subsequently allow the unlike block copolymers to demix into domains with two distinct geometries (*e.g.* cylindrical and spherical hybrid particles). In both ways, we rely on the dynamic internal nature of the aggregates so that phase separation of unlike components can take place. However, we also rely on the non-ergodic nature of the system so that molecular exchange with the solvent is limited or eliminated and, consequently, global equilibrium is not attained. These conditions guarantee that only local stability is reached within each particle, thus providing the ability to reproducibly construct the blended, multicompartment and/or multigeometry nanoparticles. This simple block copolymer blending assembly strategy provides a new paradigm for complex nanoparticle construction, materials needed for breakthroughs in medical imaging and therapy delivery as well as energy applications where multiple materials require spatial definition on the nanoscale.

A major component towards the success of our solution assembly strategy is the use of large molecular weight block copolymer amphiphiles to form nanostructures in solution. Unlike small molecule amphiphiles that are in equilibrium between the assembled and solubilized state in solution, block copolymer systems are known to be kinetically trapped in solution due to the lack of molecular chain exchange between aggregates and solution because of the large molecular weight of the assembled polymer molecules.⁸ This provides the excellent opportunity to produce molecular mixtures within individual aggregates through the correct directed or dynamic assembly technique. While a block copolymer system is unable to reach

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global equilibrium due to the lack of chain exchange with the solvent and other aggregates, changes can occur locally within aggregates. The key is to design an assembly process to confine unlike blocks, from the same copolymer or from different copolymers, into the same aggregate. Multiblock copolymer assembly (>2 blocks) is one method to produce nanostructure with multicompartments^{9–12} and can be combined with solvent mixtures¹³ or thermal transitions¹⁴ to provide kinetic control of assembled nanostructure. Other kinetic processing routes include emulsification¹⁵ or the crosslinking and dissolution of bulk block copolymer phases¹⁶ or the subsequent crystallization of blocks to form multicompartment nanostructures.¹⁷ More akin to the work presented herein, recent vesicle¹⁸ and nanoparticle^{19,20} examples reveal the type of complexity in structure made possible by diblock copolymer blending into aggregates made through kinetic control. Our kinetic control strategy provides control over the multicompartment and multigeometry nanostructure with the blending of simple diblock copolymers, clearly revealing the future complexity possible with new molecules and blends.

Kinetic control of block copolymer solution assembly is achieved with two facets: (1) solvent-directed manipulation of the pathway of molecular mixing with solvent mixtures and (2) acid/base-directed complexation of hydrophilic (water compatible) poly(acrylic acid) (PAA) blocks with multifunctional organic amines. Both facets are required together in order to produce the desired nanostructures. In this work, mixtures of two simple diblock copolymers, PAA-*b*-PS (where PS is polystyrene, a hydrophobic polymer) and PAA-*b*-PB (where PB is polybutadiene, also hydrophobic), are first dissolved in tetrahydrofuran (THF) to make a homogeneous solution. Importantly, the two different diblock copolymers both contain a PAA hydrophilic block. The critical next step is the addition of an organic diamine, 2,2'-(ethylenedioxy)diethylamine (EDDA), to the THF solution. The diamine undergoes acid–base complexation with the acid functionalities of the PAA blocks and causes the PAA blocks to aggregate.²¹ This method gives aggregates in THF with PAA–diamine cores and hydrophobic corona. Importantly, the unlike PS and PB hydrophobic block segments are confined together within the same aggregates. Moreover, because the PAA aggregation occurs in what was originally a well-solvated system, the block copolymer aggregates contain ratios of the constituent block copolymers reflecting the bulk ratios of the original mixture. This point is critical for the formation of specific compartment sizes within desired aggregates (*vide infra*). Next, water, a non-solvent for the PS and PB hydrophobic blocks, is added to the THF solution either slowly (by controlled titration) or quickly (by bulk addition). In both cases, the diblock copolymers invert, forming aggregates with hydrophobic cores of mixed PS and PB and hydrophilic shells of PAA/amine complex.

As will be shown, the diamine–polyacid complexation and selective solvent (water) addition are both critical components to the kinetic control of the assembly process. The amine–acid complexation dictates that a desired ratio of unlike block copolymer molecules is confined together through the assembly pathway described. Importantly, the complexation affords an aggregate that is globally kinetically trapped (*i.e.* no chain exchange with the solvent) but still dynamic enough so that the unlike block copolymers are able to diffuse within the aggregate. Both the confinement and internal dynamics are critical to the

formation of the complex nanoparticle structures achieved in this work.

Experimental section

Poly(acrylic acid)-*b*-polystyrene (PAA-*b*-PS) diblock copolymers

The PAA-*b*-PS diblock copolymers used in this study were synthesized by atom transfer radical polymerization (ATRP), following previous reported procedures.³³ Briefly, *tert*-butyl acrylate (*ca.* 200 equiv.) was polymerized using ethyl 2-bromopropionate (*ca.* 1.0 equiv.) as initiator, CuBr (*ca.* 1.9 equiv.) and CuBr₂ (*ca.* 0.1 equiv.) as catalysts, and *N,N,N',N',N''*-pentamethyldiethylenetriamine (PMDETA, *ca.* 2.0 equiv.) as ligand. Polymerization was performed at 50 °C and monitored by withdrawing small aliquots for GPC and NMR analyses. PtBA₉₉ was then extended into PtBA₉₉-*b*-PS₁₂₅ and PtBA₉₉-*b*-PS₇₆ in two separate reactions by further polymerizing with styrene (*ca.* 500 equiv.), using CuBr (*ca.* 3.0 equiv.) and PMDETA (*ca.* 3.0 equiv.) as catalyst and ligand, respectively, at a temperature of 55 °C. The polymerization reactions were quenched at different styrene conversions by freezing in liquid nitrogen. The *tert*-butyl-protected diblock copolymers were then transformed into PAA₉₉-*b*-PS₁₂₅ and PAA₉₉-*b*-PS₇₆ by reaction with iodotrimethylsilane (*ca.* 3.0 equiv.) following a reported deprotection protocol.²¹ The molecular characteristics of the two diblock copolymers are listed in Table 1.

Poly(acrylic acid)-*b*-polybutadiene (PAA-*b*-PB) diblock copolymers

PAA-*b*-PB diblock copolymer was purchased from Polymer Source Inc. and used as received. Composition and molecular weight were tested by ¹H NMR: PAA(5450)-*b*-PB(5600), PDI = 1.10.

Polystyrene coated-gold nanoparticles (PS-AuNPs)

Polystyrene covered gold nanoparticles were synthesized by a modified Brust method.³⁴ To synthesize the gold nanoparticles, a solution of chloroauric acid trihydrate (HAuCl₄ · 3H₂O, 56 mg) in water (4.8 mL) was added to a solution of tetraoctylammonium bromide (346 mg) in toluene (12.6 mL). The mixture was stirred vigorously until the yellow color of the aqueous phase became colorless, and the organic phase became dark red. The aqueous phase was separated, and thiol-terminated polystyrene (200 mg, *M*_n 1500 g mol^{−1}, PDI 1.1) was added to the organic phase. An aqueous solution of 0.4 M sodium borohydride (4 mL) was added slowly to the HAuCl₄/polymer mixture. The solution turned purple, and stirring was continued for several hours.

Table 1 Molecular characteristics of diblock copolymers used in this study

Sample ID	<i>N</i> _{PAA} ^a	<i>N</i> _{PS} ^a	<i>M</i> _n × 10 ⁴ Da	PDI ^b (<i>M</i> _w / <i>M</i> _n)
DE010307-11	99	125	2.03	1.08
DE010307-9	99	76	1.52	1.07

^a *N* is the degree of polymerization determined by NMR. ^b PDI was determined by GPC using polystyrene standards and THF as solvent.

Then, the aqueous phase was removed, and ethanol (500 mL) was added to the organic phase. The mixture was cooled to -30°C , and the PS-covered AuNPs were isolated by centrifugation and drying in air to give ~ 95 mg of a dark purple powder. Transmission electron micrographs of the PS-covered AuNPs were obtained on a JEOL2000EX electron microscope operated at an accelerating voltage of 200 kV. TEM samples were prepared on holey carbon substrates, with a 400 mesh grid to yield a particle size of 3.3 ± 1.4 nm as determined *via* measurement from the TEM data.

2,2'-(Ethylenedioxy)bis(ethylamine) (EDDA) is purchased from Sigma-Aldrich Corporation while tetrahydrofuran (THF) is purchased from Acros Organics.

Sample preparation

PAA-*b*-PB and PAA-*b*-PS diblock copolymers at certain blending ratio were first dissolved in THF to produce a 0.1 weight percent solution of block copolymer. Next, EDDA was added to give an amine to acid molar ratio 0.5 : 1.0. Two different methods were used for adding water into the THF solution. Slow water titration addition was performed on a syringe pump stage (KD Scientific Syringe Pump, KDS 100). 1 mL water per hour was added to 0.5 mL THF polymer solution with vigorous stirring. Fast water addition was accomplished by simply pipetting a certain amount of water into the polymer-THF solution. Afterwards, sample solutions were aged for one day before characterization.

Transmission electron microscopy (TEM)

TEM imaging was performed on a Tecnai 12 microscope operating at an accelerating voltage of 120 kV. TEM samples were prepared by applying a drop of polymer solution (about 2–4 μL) onto a carbon coated copper TEM grid and allowing the solvents to evaporate under ambient conditions. Images were collected on a Gatan CCD. A vapor staining method was applied to TEM samples. Dried TEM grids were placed on a $25 \times 75 \times 1$ mm glass slide to sit in a sealed 100 mL glass bottle suspended above 1 mL 4 wt% osmium tetroxide aqueous solution (purchased from Electron Microscopy Sciences). OsO_4 vapor staining process lasted from 6 hours to 24 hours for different samples.

Dynamic light scattering

For dynamic light scattering (DLS) experiments, equal molar PAA₇₅-*b*-PB₁₀₄ and PAA₉₉-*b*-PS₁₂₅ diblock copolymers were dissolved in pure THF to make a 0.1 wt% solution. Certain amounts of diamine (EDDA) were added into the solution and mixed to make a series of sample solutions. After filtered into 1.2 cm outer diameter glass vials, the samples were loaded in a Brookhaven Instruments BI200-SM goniometer equipped with a diode laser operated at a wavelength $\lambda = 532$ nm. Scattered light intensity I_{90° was obtained simultaneously at 90° using a Brookhaven BI-9000 correlator at room temperature.

Small angle neutron scattering

SANS experiments were performed on the 30 m instrument (NG-3) at the NIST Center for Neutron Research (NCNR),

National Institute of Standards and Technology (NIST). Samples were prepared by slowly adding certain amount of D_2O *via* titration into PAA-*b*-PS and PAA-*b*-PB blend TDF solution. Samples were loaded in titanium sample cells with 30 mm diameter quartz windows at a 2 mm path distance. Neutrons at $\lambda = 6$ Å and a wavelength spread ($\Delta\lambda/\lambda$) of 0.14 were incident on the sample. The scattered neutrons were captured by a 64 cm $\times$ 64 cm 2D detector. Sample-to-detector distances used were 1.33, 4.50, and 13.17 m to cover a scattering wavevector Q range of $0.004 < Q < 0.4$ ($\text{\AA}^{-1}$), defined by $Q = (4\pi/\lambda) \sin(\theta/2)$, where λ is the neutron wavelength and θ is the scattering angle. Sample data were corrected for background and empty cell scattering. Intensities were normalized to an absolute scale using main beam transmission measurements and were reduced according to published protocol.³⁵

Results and discussion

Fig. 1 shows the diblock copolymers used in this study, containing poly(acrylic acid) blocks of similar length for complexation with EDDA. Each diblock copolymer contains a different hydrophobic block, either PS or PB. PS and PB are well-known to be immiscible in the bulk,²² and phase-separate to nanoscale domains when connected as PS-*b*-PB diblock copolymers.^{23,24} We rely on this incompatibility for local phase separation when the PS and PB blocks are confined to the same aggregate core. While in THF solution with EDDA, the PS and PB blocks from the PAA-*b*-PS and PAA-*b*-PB diblock copolymers exist within the same aggregates, anchored there by complexation of their common PAA block chemistry with EDDA in the aggregate cores. (Evidence for the THF complexation is clearly seen in both light scattering and neutron scattering in Fig. S1 and S3†, respectively.)²⁵ When water, a selective solvent for the EDDA-complexed PAA blocks, is added quickly to give a desired ratio of 4 : 1 water to THF, the block copolymers are forced to immediately invert, thus confining the unlike PS and PB hydrophobic blocks to the common cores of the spherical aggregates, all with a PAA/amine complex shell. Once confined to the cores of these new nanoparticles, the immiscibility of the unlike PS and PB blocks becomes apparent with the local phase separation of the unlike blocks. Fig. 1a–e display the control that can be exerted over the nanoparticle morphology, afforded by the diblock copolymer blending and rapid water-induced assembly pathway. Once confined within the core of the same spherical particle, the unlike PS and PB blocks phase separate into distinct domains with relative volumes commensurate with the original block copolymer blend ratio. For this to occur, the particles must be dynamic internally in solution (provided by both the dynamic quality of the acid–base complexation of the EDDA and PAA blocks as well as the retention of THF in the solvent mixture that effectively plasticizes the hydrophobic, mixed PS and PB cores), thus allowing the diffusion of unlike block copolymers into PS and PB-rich domains within each aggregate. If no EDDA is added in the original THF solution, spherical particles are still obtained after the quick addition of water. However, the final nanoparticles have no regular, controllable internal structure (see Fig. S2†). This result illustrates that EDDA complexation is required to hold the block copolymers together in neat THF aggregates in ratios commensurate with the original block

Fig. 1 TEM images of PAA₇₅-b-PB₁₀₄ and PAA₉₉-b-PS₁₂₅ diblock copolymer blend nanoparticles formed *via* fast water addition. Nanoparticles formed in a 1 : 4 volume ratio of THF and water mixture with an amine to acid molar ratio 0.5 : 1.0. The PB phase of the nanoparticles is stained by OsO₄. Large scale bars = 100 nm. The PAA₇₅-b-PB₁₀₄ to PAA₉₉-b-PS₁₂₅ molar ratio (PB to PS volume ratio) is (a) 6 : 1 and (3 : 1); (b) 3 : 1 (3 : 2); (c) 1 : 1 (1 : 2); (d) 1 : 3 (1 : 6); and (e) 1 : 6 (1 : 12). The TEM image insets in (a)–(e) are high magnification of typical particles. Inset scale bars = 20 nm. The cartoon insets in (a)–(e) represent the approximate relative proportion of each block domain within the multi-compartment block copolymer nanoparticles. (f) The molecular structure of diblock copolymers, PAA_x-b-PS_y and PAA_m-b-PB_n, and organic diamine, EDDA, used for assembly into multi-compartment aggregates.

copolymer blend ratio. Otherwise, on water addition there is no control over the collapse of the unlike blocks into the same aggregate core for controlled multicompartment formation.

Similar local phase separation strategies are used to make colloidal particles with multicompartment cores.^{26,27} However, these colloidal processes produce larger particles (>1 μm) in the absence of significant processing²⁸ or flow.^{27,29,30} In addition, surface energy minimization of large droplets suspended in solvent gives predominantly spherical shapes to the large multi-compartment particles. With our kinetic control over the block copolymer assembly process, we can also control the shape of the final blended nanoparticle. The fact that all of the nanoparticles in Fig. 1 are spherical is a result of the specific kinetic pathway of quick addition of the aqueous selective solvent used to create the aggregates. Fig. 2 shows nanoparticles with the same relative composition of block copolymers as shown in Fig. 1. The only difference between the results in Fig. 1 and 2 is the kinetic pathway through which the aggregates were formed. While structures in Fig. 1 result from quick addition of water, those in Fig. 2 result from slow titration of the water, a non-solvent for the PB and PS blocks. While PAA-*b*-PS and PAA-*b*-PB blended particles are formed by both pathways, a critical difference is that the respective diblock copolymers are able to adopt their preferred interfacial curvature, and consequent micelle geometry, when assembled along the slow pathway. Fig. 2a and g reveal that PAA-*b*-PB and PAA-*b*-PS diblock copolymers prefer to form spherical and cylindrical particles, respectively, when assembled individually *via* slow water titration. When the two diblock copolymers are blended together and assembled *via* slow water titration, the incompatible PB and PS blocks phase

separate from one another when trapped in the same aggregate core, as also observed in Fig. 1. But now the domains rich in separated PB or PS hydrophobic block adopt a preferred interfacial curvature, spherical for the PB-containing block copolymer and cylindrical for the PS-containing block copolymer. In Fig. 2b, a 6 : 1 molar ratio of PAA-*b*-PB to PAA-*b*-PS forms spherical particles with small, internal PS domains due to the significant amount of sphere-forming PAA-*b*-PB. However, in Fig. 2c, a 3 : 1 molar blend of PAA-*b*-PB and PAA-*b*-PS is seen to form nanoparticles with small PAA-*b*-PS cylindrical midsections and PAA-*b*-PB spherical end caps on both ends. A slightly larger relative ratio of cylinder-forming PAA-*b*-PS (2 : 1 PAA-*b*-PB to PAA-*b*-PS) forms PAA-*b*-PS cylinders with only one PAA-*b*-PB cap, Fig. 2d. The remainder of the particles formed with progressively larger relative ratios of PAA-*b*-PS to PAA-*b*-PB form nanoparticles with longer and longer PAA-*b*-PS cylinder sections with a single PAA-*b*-PB end cap.

The proposed mechanism for control of phase-separated nanoparticle shape and internal morphology is shown in Fig. 2h. During a slow water titration, the block copolymers go from inverse-like aggregates in pure THF to large, long bulk phase-separated polymer particles at low to intermediate water content.³¹ With further addition of water the large particles eventually break up into the hydrophilic shell/hydrophobic core micelle-like aggregates.³¹ This transition from inverse aggregates to large, phase-separated polymer particles to micelle-like aggregates with titration of water is also observed in SANS, Fig. S3†. Prior work (as well as Fig. S3† SANS data) has shown that the phase-separated, long, large polymer particles present at low to intermediate water content exhibit a clear nanostructure

Fig. 2 TEM images of PAA₇₅-*b*-PB₁₀₄ and PAA₉₉-*b*-PS₁₂₅ diblock copolymer blend nanoparticles formed *via* slow titration water addition. Nanoparticles formed in a 1 : 4 volume ratio of THF and water mixture with an amine to acid molar ratio 0.5 : 1.0. The PB phase of the nanoparticles is stained by OsO₄. All scale bars = 100 nm. The PAA₇₅-*b*-PB₁₀₄ to PAA₉₉-*b*-PS₁₂₅ molar ratio (PB to PS volume ratio) is (a) 1 : 0 (1 : 0); (b) 6 : 1 (3 : 1); (c) 3 : 1 (3 : 2); (d) 2 : 1 (1 : 1); (e) 1 : 1 (1 : 2); (f) 1 : 3 (1 : 6); and (g) 0 : 1 (0 : 1). The TEM image insets in (b)–(e) are high magnification of typical nanoparticles. The cartoon insets in (a)–(g) represent the approximate relative proportion of each block domain within the multi-compartment, multi-geometry polymer nanoparticles. (h) The proposed mechanism of nanoparticle formation through intermediate structures with slow titration water addition.

due to the local phase separation of unlike blocks within the particles.^{25,31,32} We propose that it is this nanophase separation within the large polymer particles that makes possible the formation of multigeometry micelles that reflect the relative amounts of the unlike block copolymers in the original THF mixture prior to EDDA addition and water addition to drive assembly. The formation of the spherical particles in Fig. 2b is the simplest to rationalize since the majority copolymer in the blend that constitutes this sample is the PAA₇₅-*b*-PB₁₀₄ diblock copolymer. In these solution conditions, this diblock forms spherical micelles on its own as shown in Fig. 2a. Therefore, the majority PAA₇₅-*b*-PB₁₀₄ diblock in the PAA-*b*-PB/PAA-*b*-PS blend dictates the spherical interfacial curvature formed in the final micelle-like particle, thus forming a multicompartiment spherical particle with a small PS compartment in the dominant PB core of the spheres. With higher PAA₉₉-*b*-PS₁₂₅ content in Fig. 2c, the preferred cylindrical geometry of the PAA₉₉-*b*-PS₁₂₅ becomes apparent in the final nanoparticles. However, the still large relative ratio of PAA₇₅-*b*-PB₁₀₄ present in the system produces significant spherical geometry in the final aggregate. Therefore, as proposed in Fig. 2h, the large polymer particles with local nanophase separation at low to intermediate water content eventually pinch off into smaller nanoparticles with a cylindrical PAA₉₉-*b*-PS₁₂₅ midsection and two PAA₇₅-*b*-PB₁₀₄ spherical end caps with the addition of more water. Schematically shown in Fig. 2h, as the relative amount of PAA₉₉-*b*-PS₁₂₅ grows in the original blends, the final individual micelle-like particles grow in length due to the phase separation of unlike core PB blocks into PB-rich domains that become increasingly distant with added PAA₉₉-*b*-PS₁₂₅. However, the PAA₇₅-*b*-PB₁₀₄ regions still prefer a spherical geometry at high water content and

form spherical end-caps of increasingly longer PAA₉₉-*b*-PS₁₂₅ cylinder domains. A critical control to show that the kinetic pathway and presence of EDDA are critical for the formation of multigeometry micelles is shown in Fig. S2† where nanostructure is shown, formed from a 1 : 1 molar ratio blend of PAA₇₅-*b*-PB₁₀₄ and PAA₉₉-*b*-PS₁₂₅ in the *absence* of EDDA. Without EDDA the nanostructures formed from the blend are irregular in size, shape, and PS and PB compartment size and structure. When compared with the same blend composition and kinetic pathway but with EDDA present in Fig. 2e one can easily see the clear control of the relative PS and PB compartment size and shape and the multigeometry quality of the overall final nanoparticles afforded by the original complexation of the two diblock copolymers in the original pure THF solution.

Finally, because these hybrid particles are formed primarily with kinetic control, other block copolymers can be used to create blended micelles, and other moieties can be trapped in desired locations within the final micelle-like aggregates. Fig. 3 shows blended nanoparticles created through rapid water addition but with a different PAA-*b*-PS diblock copolymer than was used to create the particles in Fig. 1 and 2. The behaviors are nearly identical, demonstrating the more broad applicability of kinetic control in controlling nanostructure formation. Fig. 4 shows how gold nanoparticles, functionalized with PS ligands, can be trapped within the block copolymer blend nanoparticles. After mixing the functionalized gold particles into the original THF solution with both block copolymers and EDDA, water is added (slowly or quickly). The PS-coated gold nanoparticles are trapped within the hydrophobic cores of the blended nanoparticles, and further aggregate within the PS domains due to their PS coating. The potential of this technique to control block

Fig. 3 TEM images of PAA₇₅-*b*-PB₁₀₄ and PAA₉₉-*b*-PS₇₆ diblock copolymer blend nanoparticles formed *via* fast water addition. Nanoparticles formed in a 1 : 4 volume ratio of THF and water mixture with an amine to acid molar ratio 0.5 : 1.0. The PB phase of the nanoparticles is stained by OsO₄. Bottom scale bars = 100 nm. The PAA₇₅-*b*-PB₁₀₄ to PAA₉₉-*b*-PS₇₆ molar ratio (PB to PS volume ratio) is (a) 3 : 1 (3 : 1); (b) 1 : 1 (1 : 1); (c) 1 : 3 (1 : 3). The TEM image insets in (a)–(c) are high magnification of typical particles. Inset scale bars = 20 nm. The cartoon insets in (a)–(c) represent the approximate relative proportion of each block domain within the multi-compartment block copolymer nanoparticles.

Fig. 4 Hybrid nanoparticles constructed with blends of PAA₇₅-*b*-PB₁₀₄ and PAA₉₉-*b*-PS₁₂₅ and PS coated-gold nanoparticles (PS-AuNPs). The PB phase of the particles is stained by OsO₄. Scale bars = 50 nm. (a) multicompartment micelle of 1 : 1 molar blend of PAA₇₅-*b*-PB₁₀₄ and PAA₉₉-*b*-PS₁₂₅ in a 1 : 4 volume ratio of THF and water mixture with an amine to acid molar ratio 0.5 : 1.0 *via* fast water addition. White arrow points to a single PS-AuNP embedded within the PS phase of nanoparticle core. (b) PS-AuNP-loaded, multi-geometry nanoparticles of PAA₇₅-*b*-PB₁₀₄ and PAA₉₉-*b*-PS₁₂₅ blended in a 1 : 1 molar ratio in a 1 : 4 volume ratio of THF and water mixture with an amine to acid molar ratio 0.5 : 1.0 *via* slow titration water addition. The PS-AuNPs reside exclusively within the PS phase of the block copolymer nanoparticle cores.

copolymer self-assembly, and incorporate a variety of additives including small molecules, macromolecules and even nanostructures, thereby producing hybrid, multicompartment nanostructures, is thus made clear. Considering new polymer designs, the nanoscale complexity possible from dynamic solution assembly is vast and remains to be explored.

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