

Sequence-Regulated Supracolloidal Copolymers via Copolymerization-Like Coassembly of Binary Mixtures of Patchy Nanoparticles

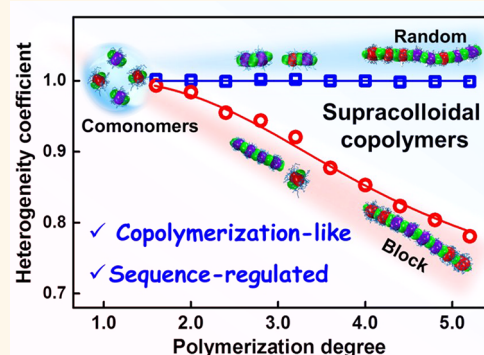
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Supporting Information

ABSTRACT: Synthetic copolymers of molecular systems serve as an inspiration for creation of one-dimensional copolymer-like superstructures via coassembly of anisometric nanoparticles. In contrast to the covalent and molecular copolymers, the details of formation mechanisms of copolymer-like superstructures, as well as the factors determining their length and the sequences of arranged nanoparticles, are still poorly understood. Herein, we propose a joint theoretical–computational framework to probe into the coassembly mechanism and kinetics of binary mixtures of patchy nanoparticles. By applying the coarse-grained molecular dynamics simulations, it is demonstrated that the coassembly of patchy nanoparticles markedly resembles many aspects of molecular step-growth copolymerization, and the sequences of nanoparticles inside the copolymer-like superstructures can be finely regulated by the relative activity and the initial ingredient of patchy nanoparticles as well as the coassembly strategy. A quantitatively copolymerization-like model is developed to account for the coassembly kinetics of patchy nanoparticles and the sequence distribution of arranged nanoparticles, all governed by the elaborate design of lower-level building units. The jointly theoretical and simulated studies offer mechanistic insights into the copolymerization-like kinetics and the sequence prediction for the coassembly of binary mixtures of patchy nanoparticles, paving the way toward the rational design of copolymer-like superstructures with various sequences and functionalities.

KEYWORDS: patchy nanoparticles, coassembly kinetics, step-growth copolymerization, sequence regulation, coarse-grained molecular dynamics



Nanoparticles often viewed as “artificial atoms” are basic building units in nanoscience for designing hierarchical superstructures with collective properties, which arise from ordered organization and coupling interactions of constituent components.^{1–4} One notable example is the self-assembled superstructures of highly anisometric nanoparticles along one-dimensional direction,^{5–11} also known as supracolloidal polymers, where the nanoparticles are linked by directional noncovalent bonds. Because of marked similarity between the molecular polymers and the supracolloidal polymers, concept of colloidal polymerization borrowing knowledge in the polymer science is proposed to design a large abundance of elaborate architectures through the self-assembly of nanoparticles with a high degree of anisometry.^{12,13} Importantly, the self-assembly kinetics of

nanoparticles and the growth pathway of their ensembles can be quantitatively predicted by the model of step-growth polymerization at the molecular level despite inherent differences between the nanoparticles and the atoms.

In light of the substantial contribution of classic polymer science to the nanoscience, it is greatly benefit from further extending the synthetic strategies of complex copolymers to the self-assembly of distinct nanoparticles.^{14–19} In comparison to the one-dimensional assembly of identical nanoparticles, the coassembly of nanoparticle’s mixtures offers structural complexities and sophisticated functionalities, which will

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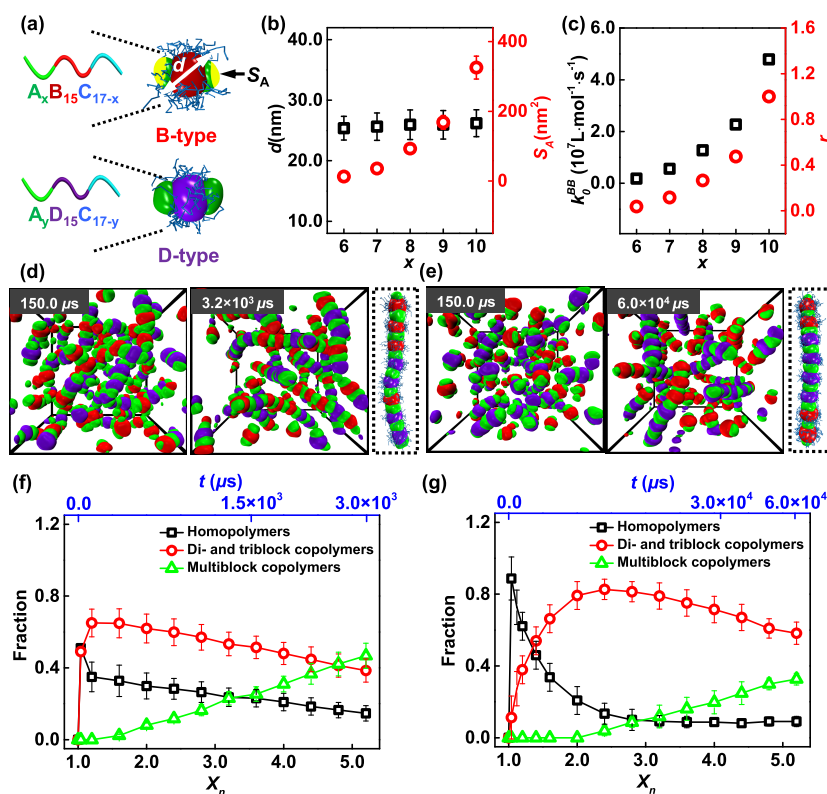


Figure 1. (a) Schematic representation of B- and D-type nanoparticles respectively formed by $A_x B_{15} C_{17-x}$ and $A_y D_{15} C_{17-y}$ triblock terpolymers. Green, red, and purple colors represent the A-, B- and D-rich solvophobic domains, respectively. The blue lines represent the solvophilic C blocks. (b) Effect of A block length x on characteristic size d of nanoparticles and exposed area S_A of A patches highlighted in panel (a). (c) Effect of A block length x on self-assembly rate constant k_0^{BB} of B-type nanoparticles and relative activity $r = k_0^{BB}/k_0^{DD}$. (d,e) Coassembled superstructures of binary mixtures of patchy nanoparticles with relative activities (d) $r = 1.00$ and (e) $r = 0.04$. Insets show typical configurations of coassembled superstructures. The initial ingredient of binary mixtures is set as $f = 0.5$. (f,g) Fractions of supracolloidal homopolymers, diblock and triblock copolymers, as well as multiblock copolymers as a function of the polymerization degree X_n . The assembly time t is annotated at the top axes. Error bars indicate the standard deviations.

expand their potential in applications and demonstrate the advantage of noncovalent synthetic approach.^{20–24} During recent years, it was experimentally observed that the binary mixtures of nanoparticles are able to coassemble into the copolymer-like superstructures and their growth is generally similar to the copolymerization of organic comonomers.^{25–29} Despite the high promises for construction of complicated superstructures, control over the sequences of arranged nanoparticles to mimic the copolymer-like architectures with tunable sequence and length is far less achieved. Precisely controlled sequences of nanoparticles inside the superstructures provide the possibility to construct artificial biopolymers such as protein and DNA, which further undergo the programmed self-organization and enable the preparation of hierarchical soft materials.^{30–32} In addition, theoretical framework that describes the underlying coassembly mechanisms and the sequence distributions of nanoparticles remains to be established. The extended knowledge of molecular copolymerization mechanisms is helpful to fundamentally capture coassembly kinetics and sequence distributions of nanoparticles; therefore, it can help the experimentalists to develop more efficient strategies of coassembly for creation of man-made nanostructured materials with promising applications in the fields of molecular sensing and bionanotechnology.

Herein, we establish a joint theoretical–computational framework to probe into the coassembly mechanism of binary mixtures of patchy nanoparticles and illustrate the sequence

control of distinct nanoparticles inside the coassembled superstructures, which are strongly analogous to molecular random and block copolymers. Specifically, the coarse-grained method is utilized to explore coassembly kinetics of binary mixtures of soft, patchy nanoparticles, as it has recently been proved to be a powerful methodology to elucidate the self-assembly kinetics of anisometric nanoparticles.^{33–37} The coarse-grained simulations explicitly demonstrate that the binary mixtures of patchy nanoparticles coassemble into the copolymer-like superstructures with widely tailored compositions and precisely controlled regularities, which are tuned by activity and the initial ingredient of building units as well as coassembly strategy. These simulation results are fully supported by the theoretical analysis of copolymerization-like kinetics. This study represents an important step toward the creation of advanced supracolloidal copolymers that are increasingly attracting attentions in recent years.

RESULTS

Our prototypical systems for the coarse-grained simulations consist of B- and D-type nanoparticles, which are respectively constructed from $A_x B_{15} C_{17-x}$ and $A_y D_{15} C_{17-y}$ triblock terpolymers via stepwise assembly strategy (Part A of Supporting Information (SI)).⁸ Herein, the subscripts x and y of nomenclatures denote the tunable length of A blocks, but the total length of triblock terpolymers is fixed at 32. As shown in Figure 1a, the nanoparticles possess two solvophobic A

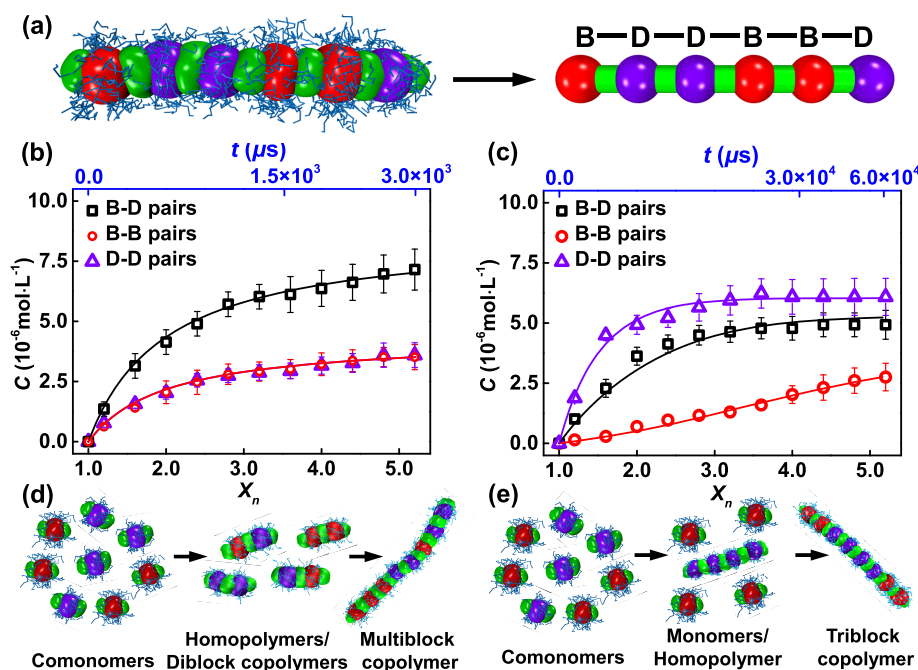


Figure 2. (a) Bead–stick representation of supracolloidal copolymers. The B–B, D–D, and B–D pairs represent the connectivity between B- and B-type, D- and D-type as well as B- and D-type nanoparticles. (b,c) Concentrations of bead–stick pairs inside the supracolloidal copolymers as a function of the polymerization degree X_n at relative activities (b) $r = 1.00$ and (c) $r = 0.04$. Solid lines denote the theoretically predicted values of eqs 2–4. (d,e) Schematic illustrations of coassembly mechanisms of binary mixtures of patchy nanoparticles.

patches on opposing sides of B or D cores, which are partially covered by the solvophilic C blocks. As the length x of A blocks is changed, the exposed area S_A (highlighted in Figure 1a) of A patches increases, but the characteristic size d of nanoparticles is invariable (Figure 1b). Such divalent patchy nanoparticles essentially behave as bifunctional monomers and irreversibly “homopolymerize” into chainlike supracolloidal polymers via attractive interaction between patches of neighboring nanoparticles (i.e., active ends of building units), which is illustrated in Part B of SI. Furthermore, the square of the number-average degree of polymerization, X_n (i.e., $X_n \equiv \sum n_i X_i / \sum n_i$, where X_i is number of nanoparticles in a single chain and n_i is number of chains containing X_i nanoparticles) grows linearly with the assembly time t , which is a qualitative feature of diffusion-controlled step-growth homopolymerization kinetics demonstrated in our previous work.³⁸ From the relationship between X_n^2 and t (i.e., $X_n^2 = 4k_0 C_0 t + 1$, where C_0 is the initial concentration of active ends of patchy nanoparticles), the self-assembly rate constant k_0 of patchy nanoparticles is estimated. As depicted in Figure 1c, the value of k_0^{BB} for homopolymerization-like process of B-type nanoparticles is boosted monotonically by prolonging the A blocks, which originates from an increase in the exposed area of solvophobic A patches. It should be mentioned that the value of k_0^{DD} for homopolymerization-like process of D-type nanoparticles is identical to the case of k_0^{BB} .

Inspired by the molecular copolymerization,¹⁴ we introduce relative activity $r = k_0^{BB}/k_0^{DD}$ to quantify the difference of self-assembly rate constants between the B- and D-type nanoparticles. For simplicity, the length of A blocks in the D-type nanoparticles is fixed at $y = 10$. As the length x of A blocks in the B-type nanoparticles is changed from 6 to 10, the relative activity r between the B- and D-type nanoparticles increases from 0.04 to 1.00 (Figure 1c). To examine the coassembly

behaviors of distinct nanoparticles, initial configurations of coarse-grained simulations contain mixtures of 120 B- and D-type monodisperse nanoparticles randomly dispersed in selective solvent (i.e., $n_0^B + n_0^D = 240$, where n_0^B and n_0^D are respectively initial numbers of active ends of B- and D-type nanoparticles), corresponding to 2.2×10^6 coarse-grained beads in the simulation boxes. Initial concentrations are denoted by $C_0^{B(D)} = n_0^{B(D)} / (N_A L^3)$, where N_A is the Avogadro constant and L is edge size of simulation box. Initial ingredient of binary mixtures is represented by $f = C_0^B / (C_0^B + C_0^D)$. For given parameter settings of simulations, 10 samples with different initial configurations are examined for statistical analysis of coassembly, and the degree of polymerization has a value of $X_n \approx 5.0$ at the end of each simulations.

Figure 1d,e shows a series of coassembled superstructures of binary mixtures of B- and D-type nanoparticles (also termed as comonomers) at relative activities $r = 1.00$ and 0.04, respectively. In general, these free comonomers have the capability to coassemble into chainlike supracolloidal copolymers consisting of a batch of B- and D-type nanoparticles. However, the sequences of coassembled nanoparticles along the chains of supracolloidal copolymers are substantially influenced by their activities. The binary mixtures of patchy nanoparticles with identical activity tend to coassemble into the supracolloidal copolymers with random sequences (Figure 1d). Under the condition of large activity difference of nanoparticles, the coassembly of binary mixtures yield the supracolloidal copolymers with specific block sequences of nanoparticles after a sufficiently long time (Figure 1e), which possess higher structural regularity in comparison with their random counterparts.

In order to gain detailed insights into the coassembly of distinct nanoparticles, it is convenient to classify the supracolloidal polymers with respect to the sequences of arranged

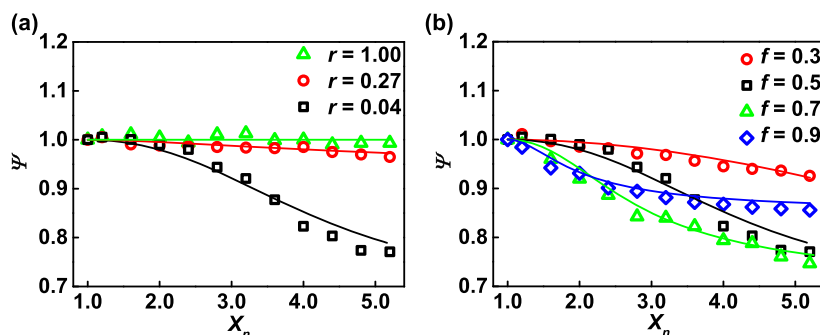


Figure 3. (a) Heterogeneity coefficient Ψ as a function of the polymerization degree X_n under different relative activities r . The initial ingredient of binary mixtures is set as $f = 0.5$. (b) Dependence of heterogeneity coefficient Ψ upon the polymerization degree X_n for different initial ingredients f at relative activities $r = 0.04$. Solid lines denote the theoretically predicted values of eqs 1–4). The error bars are not shown for clarity.

nanoparticles along the chains: homopolymers, regular diblock and triblock copolymers, as well as random multiblock copolymers. In the simulations, we keep track of the fractions of supracolloidal polymers with different sequences of nanoparticles in the course of the coassembly, which are depicted in Figure 1f,g. Note that the bottom abscissa axes are calibrated by the polymerization degree X_n , and the assembly times t are also annotated on the top axes. Under the condition of relative activity $r = 1.00$, the binary mixtures of patchy nanoparticles rapidly form hetero-oligomers with coexisting fragments of B- and D-type nanoparticles (Figure 1f). As the time goes by, such oligomers gradually evolve into the supracolloidal multiblock copolymers. Especially, the fraction of multiblock copolymers with random sequences is larger than about 0.5 at the time $t = 3.0 \times 10^3 \mu\text{s}$ (i.e., $X_n \approx 5.0$). By contrast, the systems of binary mixtures at relative activity $r = 0.04$ mainly produce the supracolloidal homopolymers in the initial stage of coassembly. In the subsequent stages, the supracolloidal diblock and triblock copolymers are the dominant components. Despite the time $t = 6.0 \times 10^4 \mu\text{s}$, the coassembly of binary mixtures yields large fraction (i.e., up to 0.6) of supracolloidal block copolymers with regular sequences. Thus, one can gain an important outcome that the nanoparticle ensembles with high degree of complexity are elaborately realized by the coassembly of divalent patchy nanoparticles with different activities.

Next, we probe into the underlying coassembly mechanisms of binary mixtures to elucidate the physical origin of complexity of nanoparticle ensembles. As schematically illustrated in Figure 2a, the supracolloidal copolymers with B- and D-type nanoparticles linked by the A patches are conceptually represented by bead–stick model of molecular polymer chains (i.e., the beads are regarded as the cores of B- or D-type nanoparticles, and the sticks signifying the linked A patches represent the connectivity of cores). Concentrations of bead–stick pairs (i.e., C_{B-B} , C_{D-D} , and C_{B-D}) for the elementary comonomers are utilized to explicate the sequences of arranged nanoparticles inside supracolloidal copolymers.

Figure 2b,c shows the concentrations of bead–stick pairs as a function of the polymerization degree X_n for the binary mixtures at relative activities $r = 1.00$ and 0.04, respectively. Figure 2d,e illustrates the corresponding coassembly mechanisms for formation of supracolloidal copolymers with various sequences. For the binary mixtures at $r = 1.00$, the concentrations of bead–stick pairs experience a simultaneous increase with X_n and gradually reach plateaus (Figure 2b).

More importantly, the concentration of B–D pairs equals the summation of B–B and D–D pairs (i.e., $C_{B-D} = C_{B-B} + C_{D-D}$), implying the incorporation of B- and D-type nanoparticles with close-to-equal amounts into the coassembled superstructures. Thus, as evident from Figures 1d and 2b, the comonomers with identical activity tend to coassemble into the supracolloidal multiblock copolymers with random sequences via the intermediate configuration of hetero-oligomers (Figure 2d). However, in the case of $r = 0.04$ the concentration of D–D pairs increases more quickly than those of B–B and B–D pairs in the initial stage of coassembly (Figure 2c), because of the higher activity of D-type nanoparticles. With the depletion of D-type nanoparticles, the concentrations of D–D and B–D pairs reach plateaus, but the concentration of B–B pairs increases continuously. Thus, the coassembly of patchy nanoparticles with larger activity difference is expected to undergo the intermediate configurations of homopolymers and finally yield the supracolloidal block copolymers with higher structural regularity (Figure 2e).

Similar to the molecular copolymers, ordering degree of patchy nanoparticles distributed inside the sophisticated supracolloidal copolymers is characterized by heterogeneity coefficient Ψ defined as³⁹

$$\Psi = \frac{C_{B-D}}{C_{B-D} + 2C_{B-B}} + \frac{C_{B-D}}{C_{B-D} + 2C_{D-D}} \quad (1)$$

The 0 and 1 values of Ψ correspond to ideal block and random copolymers, respectively. From deviation value of Ψ from unit, the ordering degree of distinct nanoparticles inside copolymer-like superstructures is quantitatively evaluated. Figure 3 shows the effects of relative activity r and initial ingredient f on the heterogeneity coefficient Ψ during the coassembly of binary mixtures. In the case of $r = 1.00$, the value of Ψ remains close to unit during the entire coassembly (Figure 3a), further demonstrating that the comonomers with identical activity coassemble into the copolymer-like superstructures with random distribution of nanoparticles. As the activity difference of patchy nanoparticles becomes large (e.g., $r = 0.04$), the value of Ψ deviates from unit, indicating that the distinct nanoparticles are regularly distributed inside the copolymer-like superstructures. In addition, the initial ingredient f of binary mixtures is able to tune the heterogeneity coefficient of supracolloidal copolymers, which is shown in Figure 3b. An excess addition of lower-activity nanoparticles (e.g., $f = 0.7$) accelerates the decrease of Ψ . However, as the value of f is too large, Ψ rapidly approaches a higher plateau and remains at

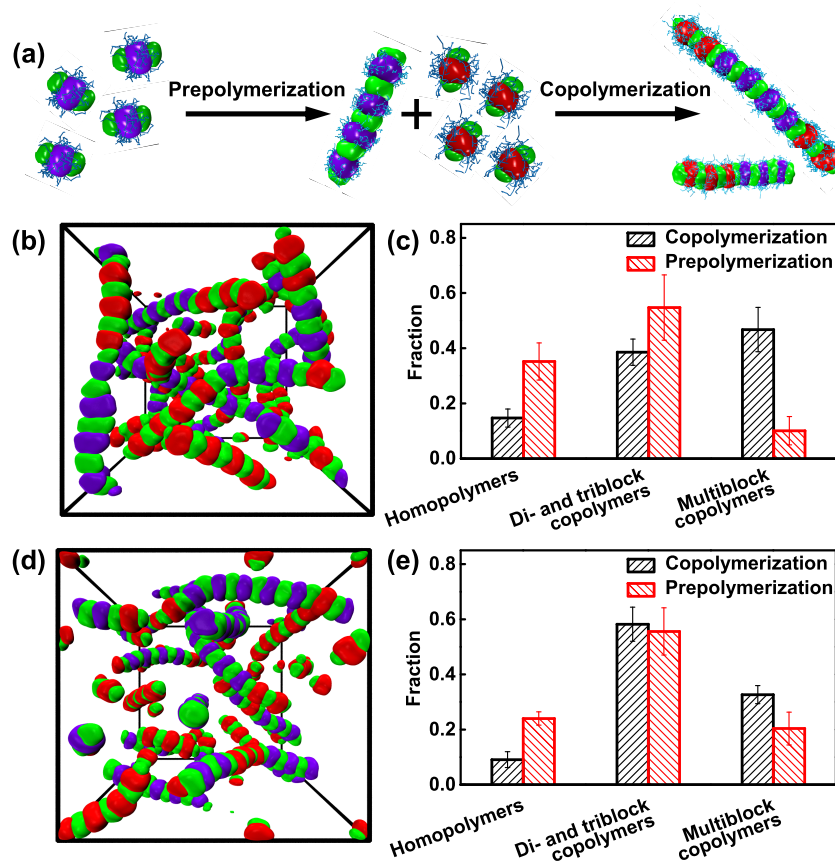


Figure 4. (a) Schematic representation of coassembly of patchy nanoparticles via prepolymerization strategy. (b,d) Coassembled superstructures of D-type prepolymer/B-type nanoparticle mixtures at relative activities (b) $r = 1.00$ and (d) $r = 0.04$. (c,e) Distributions of supracolloidal homopolymers, diblock and triblock copolymers, as well as multiblock copolymers at $X_n \approx 5.0$ for the cases of copolymerization and prepolymerization strategies.

this value at the subsequent stages of coassembly. In other words, there exists an optimum ingredient of binary mixtures to achieve the supracolloidal copolymers with higher structural regularity. Therefore, as shown in Figure 3, the sequences of arranged nanoparticles inside copolymer-like superstructures can be kinetically determined by the intrinsic coassembly of patchy nanoparticles.

In pursuit of quantitatively understanding the coassembly behaviors of binary mixtures of patchy nanoparticles, framework of copolymerization kinetics of molecular systems acquired in the polymer science is extended to predict the growth of resulting supracolloidal copolymers and the sequences of distinct nanoparticles.^{14,40} For the systems of binary mixtures of nanoparticles, it is assumed that (i) the self-assembly rate coefficient k^{IJ} ($I, J = B$ and D) is inversely proportional to the polymerization degree X_n (i.e., $k^{IJ} = k_0^{IJ}/X_n$),^{38,41,42} and (ii) the rate constant k_0^{IJ} is independent upon the penultimate nanoparticles in the copolymer-like superstructures.^{39,43} Through integrating the rate equations of coassembly, we deduce the relationship between X_n and t , namely, $X_n^2 \approx 4k_{\text{eff}}(C_0^B + C_0^D) + 1$, where the effective rate constant of coassembly is expressed as $k_{\text{eff}} = k_0^{BB}f^2 + 2k_0^{BD}f(1-f) + k_0^{DD}(1-f)^2$. A fitting of simulation data to the deduced relationship yields the value of k_{eff} . Importantly, the rate constant k_0^{BD} for heteropolymerization-like process between the B- and D-type nanoparticles is estimated from k_{eff} in terms of the initial ingredient f . For instance, the rate constants for homopolymerization-like processes of B- and D-type nano-

particles in the case of $r = 0.04$ are found to be $k_0^{BB} = 0.19 \times 10^7 \text{ L}\cdot\text{mol}^{-1}\cdot\text{s}^{-1}$ and $k_0^{DD} = 4.79 \times 10^7 \text{ L}\cdot\text{mol}^{-1}\cdot\text{s}^{-1}$, respectively. The rate constant $k_0^{BD} = 0.63 \times 10^7 \text{ L}\cdot\text{mol}^{-1}\cdot\text{s}^{-1}$ for heteropolymerization-like process is intermediate between the homopolymerization rate constants and is estimated by the “mixing rule” of $k_0^{BD} \approx \sqrt{k_0^{BB} \times k_0^{DD}}$. Full details regarding the theoretical model and the estimation of rate constants are provided in Part C of SI.

On the basis of the rate constants k_0^{BB} , k_0^{DD} , and k_0^{BD} , the sequences of arranged nanoparticles inside the coassembled superstructures can be predicted from rate equations of bead–stick pairs given by^{14,44}

$$\frac{dC_{B-B}}{dt} = k^{BB}C_B^2 \quad (2)$$

$$\frac{dC_{D-D}}{dt} = k^{DD}C_D^2 \quad (3)$$

$$\frac{dC_{B-D}}{dt} = 2k^{BD}C_B C_D \quad (4)$$

where $C_B = C_0^B - 2C_{B-B} - C_{B-D}$ and $C_D = C_0^D - 2C_{D-D} - C_{B-D}$ are respectively concentrations of residual B- and D-type active ends at the assembly time t . By substituting the rate constants and the initial concentrations of active ends, numerical solutions of the above equations yield the concentrations of bead–stick pairs and the heterogeneity coefficient of eq 1 in the course of copolymerization-like process, which are

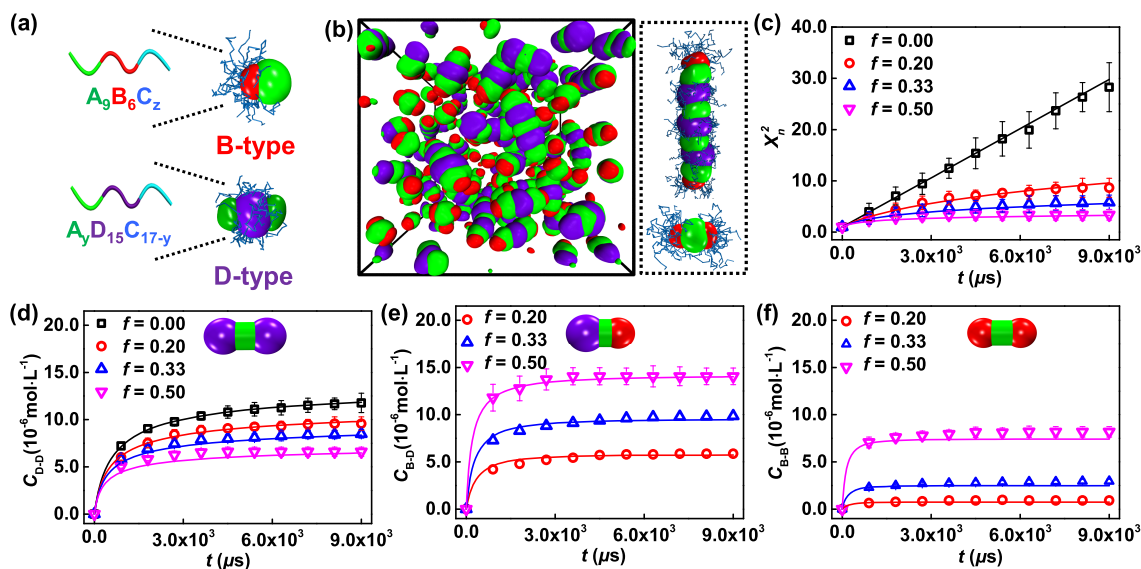


Figure 5. Coassembly of monovalent and divalent patchy nanoparticles. (a) Schematic representation of monovalent B-type and divalent D-type nanoparticles respectively formed by $A_9B_6C_z$ and $A_yD_{15}C_{17-y}$ triblock terpolymers. (b) Coassembled superstructures of binary mixtures of monovalent and divalent patchy nanoparticles at initial ingredient $f = 0.50$ and relative activity $r = 2.5$. Insets show typical configurations of coassembled superstructures. (c) Square X_n^2 of number-average degree of polymerization as a function of the assembly time t under various initial ingredients f of binary mixtures. (d–f) Concentrations of D–D, B–D, and B–B bead–stick pairs as a function of the assembly time t . Solid lines denote the theoretically predicted values of eqs 2–4. Insets illustrate the representations of bead–stick pairs.

respectively presented by the solid lines in Figures 2 and 3. The good agreement between the theoretical values and the simulation data suggests the fact that the coassembly kinetics of distinct nanoparticles satisfies the extended copolymerization-like model, and the sequences of distinct nanoparticles inside supracolloidal copolymers can be manipulated by the physicochemical properties of lower-level building units (e.g., the block length of triblock terpolymers and the initial ingredient of binary mixtures).

Finally, considering the fundamental resemblance between coassembly of patchy nanoparticles and copolymerization of molecular comonomers, prepolymerization strategy used in synthesis of molecular block copolymers is proposed to enable the growth of sophisticated supracolloidal copolymers with elaborately designed sequences. In the coarse-grained simulations, 60 D-type nanoparticles first preassemble into homopolymers with prepolymerization degree $X_n^0 = 3.0$, and then are mixed with 60 B-type nanoparticles, which are schematically illustrated in Figure 4a. The relative activity of B- and D-type nanoparticles has a value of $r = 1.00$. Interestingly, unlike the aforementioned random copolymers obtained from simple copolymerization-like process (Figure 1d),^{45,46} the block copolymer-like superstructures with regular arrangement of nanoparticles are achieved by the prepolymerization strategy (Figure 4b and Part D of SI). The statistical analysis clearly demonstrates that the supracolloidal diblock and triblock copolymers constitute majority of coassembled superstructures (Figure 4c). The heterogeneity coefficient Ψ has a value of 0.40, somewhat deviating from the value of zero expected for ideal block copolymer-like superstructures. Further increase of prepolymerization degree of supracolloidal homopolymers could help to improve the quality of block copolymer-like superstructures through lowering contribution of imperfectly supracolloidal multiblock copolymers (Figure S7 in Part D of SI). Impressively, the prepolymerization strategy can be readily generalized to the growth of supracolloidal copolymers for the

case of $r = 0.04$. As shown in Figure 4d,e, a large fraction of block copolymer-like superstructures with regular sequences are also achieved by this strategy. Furthermore, separate simulations for the systems of B-type prepolymer/D-type nanoparticle mixtures confirm the fact that the prepolymerization strategy has the capability to yield the one-dimensional supracolloidal copolymers with higher regularity.

The simulation method and the theoretical model presented above can be applied to the mesoscopic systems of divalent nanoparticles in the presence of monovalent nanoparticles.^{44,47,48} Herein, we construct monovalent B-type nanoparticles from $A_9B_6C_z$ triblock copolymers with various length z of solvophilic C blocks (Figure 5a). As shown in Part E of SI, monovalent B-type nanoparticles self-assemble into the inverse dimers possessing terminations of solvophilic C blocks, and their self-assembly rate constants k_0^{BB} are regulated by the length z of C blocks. In the system of binary mixtures of monovalent and divalent patchy nanoparticles, the monovalent B-type nanoparticles act as “chain stoppers” to suppress the growth of polymer-like superstructures (Figure 5b,c), which are tuned by varying the amount of monovalent nanoparticles. Such coassembly behaviors can be understood from the concentrations of D–D, B–D, and B–B bead–stick pairs in terms of the assembly time (Figure 5d–f and Part F of SI). With an increase of the amount of monovalent B-type nanoparticles, the formation probabilities of B–D and B–B bead–stick pairs are boosted, leading to a decrease in concentration of D–D pairs and length of supracolloidal polymers at given time. More importantly, the numerical results of eqs 2–4 agree well with the simulation data, indicating that the conceptual framework of copolymerization-like kinetics can be potentially generalized to a broad scope of coassembly kinetics of nanosized objects such as mixtures of patchy nanoparticles with various valences.

DISCUSSION

The quantitative match of simulation results with theoretical predictions supports the hypothesis that the coassembly of highly anisometric nanoparticles resembles many aspects of molecular step-growth copolymerization, such as the comonomers \rightarrow oligomer \rightarrow copolymer pathway (Figures 1 and 2) and the dependence of comonomer sequences inside the chains upon their relative activities (Figure 3). These resemblances between copolymerization of molecular monomers and coassembly of patchy nanoparticles offer a mutually beneficial strategy that enriches both the knowledge of nanoscience and polymer science. On one hand, the copolymerization approach developed in the polymer science provides an elegant example for enabling quantitative control over the structural characteristics of coassembled superstructures such as their length and sequence distribution of arranged nanoparticles. On the other hand, the capability to identify and analyze emerging superstructures of nanoparticle ensembles through the coarse-grained molecular dynamics simulations provides a reliable route to probe into the copolymerization kinetics of molecular monomers, e.g., mechanism of chemical reactions and molecular design of comonomers. Thus, this study goes beyond previous features of molecular polymerization and provides useful information about the coassembly of patchy nanoparticles.

Despite the physical analogies to the molecular step-growth copolymerization, there also exist some distinctive characteristics in the course of coassembly of distinct nanoparticles, which are not possessed in the systems of molecular comonomers and other mixtures of anisometric nanoparticles. Namely, the architectures of supracolloidal copolymers are easily tuned from random to block sequences, which can be directly controlled by the block length of molecular triblock terpolymers. Specifically, the tailored triblock terpolymers hierarchically self-assemble into the divalent patchy nanoparticles with equivalent size but different activities, which are respectively demonstrated in Figure 1b,c. Instead of the supracolloidal random copolymers,^{45,46} the patchy nanoparticles with equivalent size are able to coassemble into the block copolymer-like superstructures with higher regularity (case of $r = 0.04$ in Figures 1 and 3). This fact points out the ability to regulate the sequences of nanoparticles with equivalent size.

The results presented here will provide an unusual perspective on the kinetic control over the spatial organization of patchy nanoparticles inside one-dimensional supracolloidal copolymers. Currently, there exist thermodynamic methods for generating the sequence distributions of nanoparticles inside the superstructures,^{20,33,49} which rely strictly on the specific interactions of selected nanoparticles. However, the sequences of arranged nanoparticles inside the resulting superstructures are not readily to be controlled through the thermodynamic approaches, because the interaction-specified systems are easy to trap into the metastable configurations. In contrast, we elaborately propose a strategy of hierarchical self-assembly to build upon the patchy nanoparticles with various valences, whose patches are constructed from the identical components of triblock terpolymers. It is demonstrated that the selected sequences of patchy nanoparticles are achieved by manipulating the formation rate of bead–stick pairs instead of the pairwise interaction between distinct nanoparticles, as a result of changing the relative activity, the initial ingredient as well as

the coassembly strategy. Such kinetic approach represents an important step toward rational and precise design of one-dimensional sequence-regulated superstructures with promising horizons for biomedical applications.

CONCLUSIONS

In summary, by coupling the coarse-grained molecular dynamics simulations with the theoretical analysis, we bridge the gap between copolymerization reaction taking place at molecular level and nanoparticle coassembly occurring at mesoscopic scale. It is definitely demonstrated that the binary mixtures of patchy nanoparticles are able to coassemble into the copolymer-like superstructures with widely tailored sequences and compositions, which are manipulated by their relative activity and initial ingredient as well as coassembly strategy. Furthermore, the coassembly kinetics and the sequence distribution of nanoparticles can be predicted by the extended step-growth copolymerization model originally proposed in the community of polymer science. These findings enrich the design rules and quantitative predictions for the coassembly of anisometric nanoparticles, which significantly prompt experimental realization of hierarchical superstructures with controllable sequences through mimicking a large library of macromolecules.

METHODS

Coarse-Grained Molecular Dynamics Simulations. The dissipative particle dynamics (DPD) is extended to investigate the coassembly behaviors of anisometric nanoparticles,⁵⁰ which are constructed from the self-assembly of triblock terpolymers. These polymers (designated as ABC or ADC) correspond to the polystyrene-*block*-polybutadiene-*block*-poly(methyl methacrylate) used in the Müller's group.^{8,25} The interaction parameters between various components are deduced from the Flory–Huggins interaction parameters, which are obtained via the atomistic molecular dynamics simulations of pure and binary systems.³⁸ Figure S1 of SI depicts the procedures of DPD simulations for the hierarchical self-assembly of $A_xB_{15}C_{17-x}$ and $A_yD_{15}C_{17-y}$ triblock terpolymers (subscripts x and y denote the tunable lengths of A blocks). In the first step of our simulations, the B- and D-type patchy nanoparticles of triblock terpolymers are achieved via the stepwise assembly strategy. In the second step, mixtures of B- and D-type patchy nanoparticles are used to probe into their coassembly behaviors. More details on the simulation method are given in Part A of SI.

Copolymerization-like Kinetics of Coassembly. Herein, the coassembly of binary mixtures of divalent B- and D-type nanoparticles is chosen as a representative example to illustrate the theoretical model of copolymerization-like kinetics, which is extended from the copolymerization model of molecular comonomers.⁴⁰ The B- and D-type patchy nanoparticles with the binding capabilities on their two active ends are equivalent to molecular monomers with two functional groups in the polymerization reaction. By assuming that the rate constants of coassembly are independent upon the penultimate nanoparticles in the copolymer-like superstructures, consumptions of B- and D-type active ends are expressed by the rate equations. Integrating the rate equations yields the analytic expressions of the number-average degree of polymerization. Full details regarding the theoretical model are provided in Part C of SI. The polymerization-like models for the self-assembly of divalent patchy nanoparticles and the coassembly of monovalent/divalent nanoparticle's mixtures are also given in Parts B and F of SI, respectively.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsnano.8b08431.

Model and additional simulation results (PDF)

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Notes

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REFERENCES

- (1) Glotzer, S. C.; Solomon, M. J. Anisotropy of Building Blocks and Their Assembly into Complex Structures. *Nat. Mater.* **2007**, *6*, 557–562.
- (2) Liu, K.; Zhao, N.; Kumacheva, E. Self-Assembly of Inorganic Nanorods. *Chem. Soc. Rev.* **2011**, *40*, 656–671.
- (3) Walther, A.; Müller, A. H. E. Janus Particles: Synthesis, Self-Assembly, Physical Properties, and Applications. *Chem. Rev.* **2013**, *113*, 5194–5261.
- (4) Hill, L. J.; Pinna, N.; Char, K.; Pyun, J. Colloidal Polymers from Inorganic Nanoparticle Monomers. *Prog. Polym. Sci.* **2015**, *40*, 85–120.
- (5) Akcora, P.; Liu, H.; Kumar, S. K.; Moll, J.; Li, Y.; Benicewicz, B. C.; Schadler, L. S.; Acehin, D.; Panagiotopoulos, A. Z.; Pryamitsyn, V.; Ganesan, V.; Ilavsky, J.; Thiagarajan, P.; Colby, R. H.; Douglas, J. F. Anisotropic Self-Assembly of Spherical Polymer-Grafted Nanoparticles. *Nat. Mater.* **2009**, *8*, 354–359.
- (6) Chen, Q.; Whitmer, J. K.; Jiang, S.; Bae, S. C.; Luijten, E.; Granick, S. Supracolloidal Reaction Kinetics of Janus Spheres. *Science* **2011**, *331*, 199–202.
- (7) Wang, Y.; Wang, Y.; Breed, D. R.; Manoharan, V. N.; Feng, L.; Hollingsworth, A. D.; Weck, M.; Pine, D. J. Colloids with Valence and Specific Directional Bonding. *Nature* **2012**, *491*, 51–55.
- (8) Gröschel, A. H.; Schacher, F. H.; Schmalz, H.; Borisov, O. V.; Zhulina, E. B.; Walther, A.; Müller, A. H. E. Precise Hierarchical Self-Assembly of Multicomponent Micelles. *Nat. Commun.* **2012**, *3*, 710.
- (9) Gao, B.; Arya, G.; Tao, A. R. Self-Orienting Nanocubes for the Assembly of Plasmonic Nanojunctions. *Nat. Nanotechnol.* **2012**, *7*, 433–437.
- (10) Kim, J.-H.; Kwon, W. J.; Sohn, B.-H. Supracolloidal Polymer Chains of Diblock Copolymer Micelles. *Chem. Commun.* **2015**, *51*, 3324–3327.
- (11) Kim, J.; Ou, Z.; Jones, M. R.; Song, X.; Chen, Q. Imaging the Polymerization of Multivalent Nanoparticles in Solution. *Nat. Commun.* **2017**, *8*, 761.
- (12) Liu, K.; Nie, Z.; Zhao, N.; Li, W.; Rubinstein, M.; Kumacheva, E. Step-Growth Polymerization of Inorganic Nanoparticles. *Science* **2010**, *329*, 197–200.
- (13) Yang, C.; Ma, X.; Lin, J.; Wang, L.; Lu, Y.; Cai, C.; Zhang, L.; Gao, L. Supramolecular “Step Polymerization” of Preassembled Micelles: A Study of “Polymerization” Kinetics. *Macromol. Rapid Commun.* **2018**, *39*, 1700701.
- (14) Odian, G. *Principles of Polymerization*; John Wiley & Sons, Inc.: Hoboken, NJ, 2004.
- (15) Hadjichristidis, N. *Block Copolymers*; Wiley: New York, 2002.
- (16) Nakatani, K.; Ogura, Y.; Koda, Y.; Terashima, T.; Sawamoto, M. Sequence-Regulated Copolymers via Tandem Catalysis of Living Radical Polymerization and *in situ* Transesterification. *J. Am. Chem. Soc.* **2012**, *134*, 4373–4383.
- (17) Zhao, Y.; Xu, L.; Liz-Marzán, L. M.; Kuang, H.; Ma, W.; Asenjo-García, A.; García de Abajo, F. J.; Kotov, N. A.; Wang, L.; Xu, C. Alternating Plasmonic Nanoparticle Heterochains Made by Polymerase Chain Reaction and Their Optical Properties. *J. Phys. Chem. Lett.* **2013**, *4*, 641–647.
- (18) Finnegan, J. R.; Lunn, D. J.; Gould, O. E. C.; Hudson, Z. M.; Whittell, G. R.; Winnik, M. A.; Manners, I. Gradient Crystallization-Driven Self-Assembly: Cylindrical Micelles with “Patchy” Segmented Coronas via the Coassembly of Linear and Brush Block Copolymers. *J. Am. Chem. Soc.* **2014**, *136*, 13835–13844.
- (19) Jung, S. H.; Boichichio, D.; Pavan, G. M.; Takeuchi, M.; Sugiyasu, K. A Block Supramolecular Polymer and Its Kinetically Enhanced Stability. *J. Am. Chem. Soc.* **2018**, *140*, 10570–10577.
- (20) Whitelam, S.; Schulman, R.; Hedges, L. Self-Assembly of Multicomponent Structures in and out of Equilibrium. *Phys. Rev. Lett.* **2012**, *109*, 265506.
- (21) Görl, D.; Zhang, X.; Stepanenko, V.; Würthner, F. Supramolecular Block Copolymers by Kinetically Controlled Co-Self-Assembly of Planar and Core-Twisted Perylene Bisimides. *Nat. Commun.* **2015**, *6*, 7009.
- (22) Das, A.; Vantomme, G.; Markvoort, A. J.; Ten Eikelder, H. M. M.; Garcia-Iglesias, M.; Palmans, A. R. A.; Meijer, E. W. Supramolecular Copolymers: Structure and Composition Revealed by Theoretical Modeling. *J. Am. Chem. Soc.* **2017**, *139*, 7036–7044.
- (23) Adelizzi, B.; Aloï, A.; Markvoort, A. J.; Ten Eikelder, H. M. M.; Voets, I. K.; Palmans, A. R. A.; Meijer, E. W. Supramolecular Block Copolymers under Thermodynamic Control. *J. Am. Chem. Soc.* **2018**, *140*, 7168–7175.
- (24) Thota, B. N. S.; Lou, X.; Boichichio, D.; Paffen, T. F. E.; Lafleur, R. P. M.; von Dongen, J. L. J.; Ehrmann, S.; Haag, R.; Pavan, G. M.; Palmans, A. R. A.; Meijer, E. W. Supramolecular Copolymerization as a Strategy to Control the Stability of Self-Assembled Nanofibers. *Angew. Chem., Int. Ed.* **2018**, *57*, 6843–6847.
- (25) Gröschel, A. H.; Walther, A.; Löbbling, T. I.; Schacher, F. H.; Schmalz, H.; Müller, A. H. E. Guided Hierarchical Co-Assembly of Soft Patchy Nanoparticles. *Nature* **2013**, *503*, 247–251.
- (26) Liu, K.; Lukach, A.; Sugikawa, K.; Chung, S.; Vickery, J.; Therien-Aubin, H.; Yang, B.; Rubinstein, M.; Kumacheva, E. Copolymerization of Metal Nanoparticles: A Route to Colloidal Plasmonic Copolymers. *Angew. Chem., Int. Ed.* **2014**, *53*, 2648–2653.
- (27) Pavlopoulos, N. G.; Dubose, J. T.; Hartnett, E. D.; Char, K.; Pyun, J. Colloidal Random Terpolymers: Controlling Reactivity Ratios of Colloidal Comonomers via Metal Tipping. *ACS Macro Lett.* **2016**, *5*, 950–954.
- (28) Luo, B.; Simth, J. W.; Wu, Z.; Kim, J.; Ou, Z.; Chen, Q. Polymerization-Like Co-Assembly of Silver Nanoplates and Patchy Spheres. *ACS Nano* **2017**, *11*, 7626–7633.
- (29) Zhang, X.; Lv, L.; Wu, G.; Yang, D.; Dong, A. Cluster-Mediated Assembly Enables Step-Growth Copolymerization from Binary Nanoparticle Mixtures with Rationally Designed Architectures. *Chem. Sci.* **2018**, *9*, 3986–3991.
- (30) Lutz, J. F.; Lehn, J. M.; Meijer, E. W.; Matyjaszewski, K. From Precision Polymers to Complex Materials and Systems. *Nature Reviews Materials* **2016**, *1*, 16024.
- (31) Guo, D.; Li, Y.; Zheng, X.; Li, F.; Chen, S.; Li, M.; Yang, Q.; Li, H.; Song, Y. Programmed Coassembly of One-Dimensional Binary Superstructures by Liquid Soft Confinement. *J. Am. Chem. Soc.* **2018**, *140*, 18–21.
- (32) Xu, J. P.; Zhou, H.; Yu, Q.; Manners, I.; Winnik, M. A. Competitive Self-Assembly Kinetics as a Route to Control the Morphology of Core-Crystalline Cylindrical Micelles. *J. Am. Chem. Soc.* **2018**, *140*, 2619–2628.
- (33) Ruiz, L.; Keten, S. Thermodynamics versus Kinetics Dichotomy in the Linear Self-Assembly of Mixed Nanoblocks. *J. Phys. Chem. Lett.* **2014**, *5*, 2021–2026.
- (34) Jiang, S.; Yan, J.; Whitmer, J. K.; Anthony, S. M.; Luijten, E.; Granick, S. Orientationally Glassy Crystals of Janus Spheres. *Phys. Rev. Lett.* **2014**, *112*, 218301.

- (35) Benjamin, A.; Keten, S. Polymer Conjugation as a Strategy for Long-Range Order in Supramolecular Polymers. *J. Phys. Chem. B* **2016**, *120*, 3425–3433.
- (36) Zhou, Y.; Ma, X.; Zhang, L.; Lin, J. Directed Assembly of Functionalized Nanoparticles with Amphiphilic Diblock Copolymers. *Phys. Chem. Chem. Phys.* **2017**, *19*, 18757–18766.
- (37) Bochicchio, D.; Pavan, G. M. From Cooperative Self-Assembly to Water-Soluble Supramolecular Polymers Using Coarse-Grained Simulations. *ACS Nano* **2017**, *11*, 1000–1011.
- (38) Ma, X.; Zhou, Y.; Zhang, L.; Lin, J.; Tian, X. Polymerization-Like Kinetics of the Self-Assembly of Colloidal Nanoparticles into Supracolloidal Polymers. *Nanoscale* **2018**, *10*, 16873–16880.
- (39) Kuchanov, S.; Slot, H.; Stroeks, A. Development of a Quantitative Theory of Polycondensation. *Prog. Polym. Sci.* **2004**, *29*, 563.
- (40) Flory, P. *Principles of Polymer Chemistry*; Cornell University Press: Ithaca, NY, 1953.
- (41) Doi, M. Diffusion-Controlled Reaction of Polymers. *Chem. Phys.* **1975**, *9*, 455–466.
- (42) Guzmán, J. D.; Pollard, R.; Schieber, J. D. Modeling of Diffusion Effects on Step- Growth Polymerizations. *Macromolecules* **2005**, *38*, 188–195.
- (43) Suter, U. W.; Pino, P. Structural Isomerism in Polycondensates. 2. Aspects for Monomers with Independent Functional Groups. *Macromolecules* **1984**, *17*, 2248–2255.
- (44) Klinkova, A.; Thérien-Aubin, H.; Choueiri, R. M.; Rubinstein, M.; Kumacheva, E. Colloidal Analogs of Molecular Chain Stoppers. *Proc. Natl. Acad. Sci. U. S. A.* **2013**, *110*, 18775–18779.
- (45) Wang, H.; Song, X.; Liu, C.; He, J.; Chong, W. H.; Chen, H. Homo- and Co-polymerization of Polystyrene-*block*-Poly(acrylic acid)-Coated Metal Nanoparticles. *ACS Nano* **2014**, *8*, 8063–8073.
- (46) Bannwarth, M. B.; Utech, S.; Ebert, S.; Weitz, D. A.; Crespy, D.; Landfester, K. Colloidal Polymers with Controlled Sequence and Branching Constructed from Magnetic Field Assembled Nanoparticles. *ACS Nano* **2015**, *9*, 2720–2728.
- (47) Knoblen, W.; Besseling, N. A. M.; Cohen Stuart, M. A. Chain Stoppers in Reversible Supramolecular Polymer Solutions Studied by Static and Dynamic Light Scattering and Osmometry. *Macromolecules* **2006**, *39*, 2643–2653.
- (48) Smulders, M. M. J.; Nieuwenhuizen, M. M. L.; Grossman, M.; Filot, I. A. W.; Lee, C. C.; de Greef, T. F. A.; Schenning, A. P. H. J.; Palmans, A. R. A.; Meijer, E. W. Cooperative Two-Component Self-Assembly of Mono- and Ditopic Monomers. *Macromolecules* **2011**, *44*, 6581–6587.
- (49) Di Michele, L.; Varrato, F.; Kotar, J.; Nathan, S. H.; Foffi, G.; Eiser, E. Multistep Kinetic Self-Assembly of DNA-Coated Colloids. *Nat. Commun.* **2013**, *4*, 2007.
- (50) Groot, R.; Warren, P. Dissipative Particle Dynamics: Bridging the Gap between Atomistic and Mesoscopic Simulation. *J. Chem. Phys.* **1997**, *107*, 4423–4435.