

## Three-Dimensional Lock and Key Colloids

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**S** Supporting Information

**ABSTRACT:** Colloids with well-defined multicavities are synthesized through the hydrolytic removal of silica cluster templates from organo-silica hybrid patchy particles. The geometry of the cavities stems from the originally assembled cluster templates, displaying well-defined three-dimensional symmetries, ranging from spherical, linear, triangular, tetrahedral, trigonal dipyramidal, octahedral, to pentagonal dipyramidal. The concave surface of the cavities is smooth, and the cavity shallowness and size can be varied. These particles with multicavities can act as “lock” particles with multiple “key holes”. Up to  $n$  “key” particles can self-assemble into the lock particles via depletion interaction, resulting in multivalent, site-specific, reversible, and flexible bonding.

Introducing specific directional interactions between colloids has the potential to programmably assemble colloids into complex architectures for applications in photonics, plasmonics, or catalysis.<sup>1–5</sup> A number of binding schemes have been explored in colloidal science<sup>6–12</sup> in which short-ranged attractions, driven by surface chemistry, are used to assemble particles together while bond directionality is endowed through particle anisotropy. For example, carbon chains functionalized at the patches of triblock Janus particles can induce patch–patch attractions based on hydrophobic interactions, leading to the assembly of a Kagome lattice.<sup>7</sup> Other examples involve the use of DNA hybridization or metal coordination, coupled with various anisotropic colloids such as patchy<sup>8,9</sup> and faceted particles.<sup>10,11</sup>

Inspired by Emil Fischer’s lock-and-key principle,<sup>13</sup> we have developed an alternative binding strategy that can afford directional specific interactions exploiting complementary shapes.<sup>14</sup> Using colloidal particles with a spherical cavity as locks and spheres as keys, we demonstrated that the keys exhibiting a size that matches the lock cavities can bind to the cavity through depletion interactions. This lock-and-key binding is reversible, flexible, and independent of the nature of the colloidal particles and their surface chemistry. These features make this strategy an attractive way to assemble structures with interchangeable configurations and variable materials compositions.

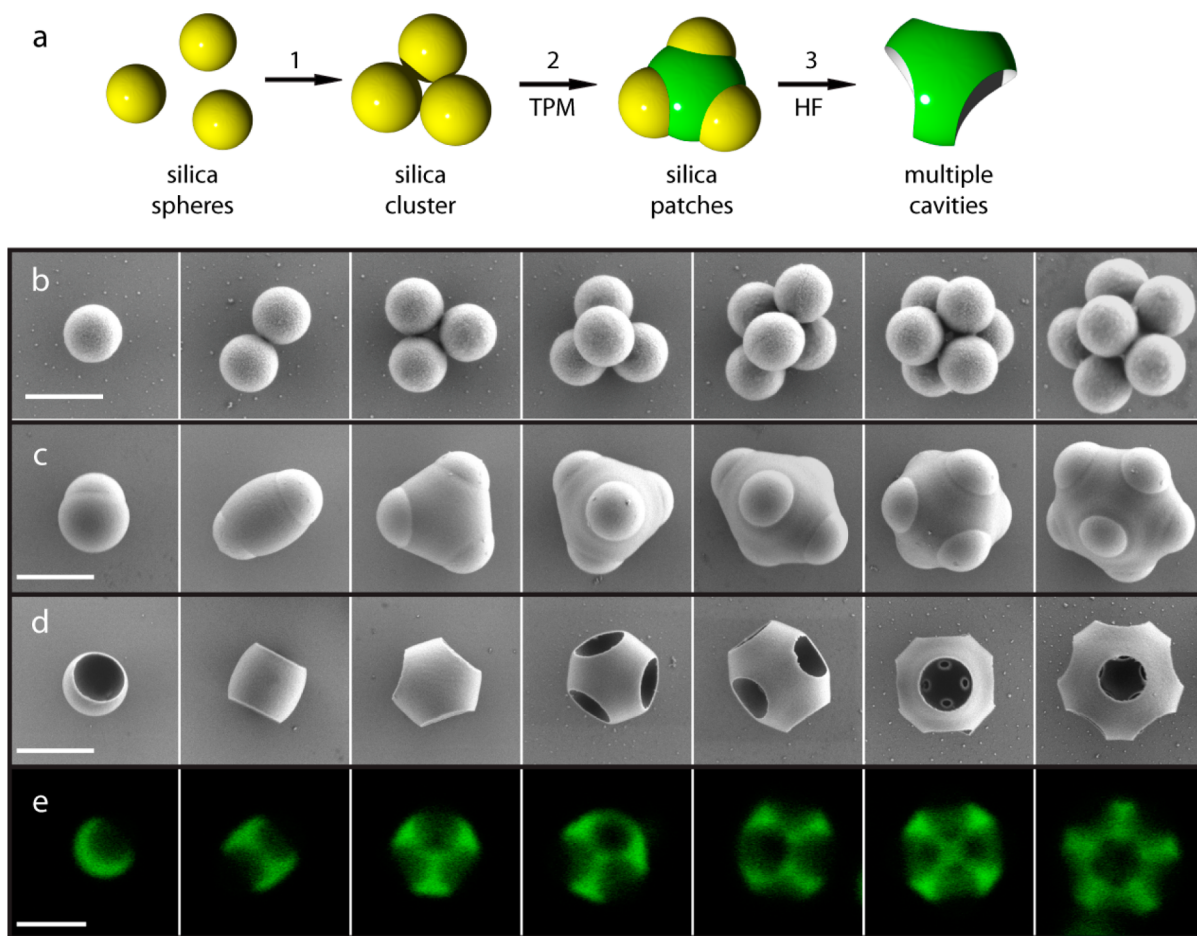
Previously, we demonstrated that the lock colloids can accommodate a single key particle (monovalent), thus limiting particle bonding to one direction. To produce complex colloidal architectures, both finite structures, such as colloidal molecules, and extended crystalline arrays, such as the diamond lattice, the realization of multiple directional interactions is a prerequisite. This requires the fabrication of lock particles with multiple cavities that can undergo depletion attractions based on shape complementarity. The number of the cavities on each lock particle determines the number of bonds (multivalency) whereas the symmetry of the cavities determines the bonding geometry.

Colloids with a single cavity can be obtained in high yield and uniform sizes through controlled bulk processes.<sup>14–16</sup> This method, however, cannot be extended to prepare multicavity particles. A promising approach is to prepare biphasic colloids and selectively remove one component using calcinations or chemical etching. Several kinds of multicavity particles have been fabricated via this approach, such as a hollow silica shell with 1–8 cavities,<sup>17</sup> poly(styrene) particles with two or three cavities,<sup>18</sup> and silica particles with tetra-, hexa-, and dodecavities.<sup>19</sup> None of these hollow particles, however, exhibits micrometer sized cavities with well-defined morphology and symmetries: multivalent lock and key based self-assembly has yet to be demonstrated.<sup>20</sup>

Here, we report the synthesis of colloids with a specific number of cavities ( $n = 1–7$  and more) that display well-defined symmetries, ranging from spherical, linear, triangular, tetrahedral, trigonal dipyramidal, octahedral, to pentagonal dipyramidal. Our strategy is based on partial encapsulation of silica clusters with 3-(trimethoxysilyl)propyl methacrylate (TPM, Scheme S1) into hybrid patchy particles followed by the selective removal of the silica. The resulting cavities exhibit smooth inner surfaces. Particle morphologies and sizes can be readily controlled by varying patchy particle fabrication conditions. As a proof of concept, we show that these particles can act as “locks” with  $n$  “key holes” and assemble with up to  $n$  “key” particles via depletion interactions, forming colloidal molecules with well-defined 3D geometries. Our strategy, exploiting multivalency<sup>21</sup> and directional interactions based on

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**Figure 1. Multicavity particle fabrication.** (a) Preparation of colloidal particles with multiple cavities having well-defined symmetries. A three-cavity particle is shown as an example. 1. A cluster of three silica spheres is prepared via an emulsion–encapsulation process. 2. Partial encapsulation of the cluster with 3-(trimethoxysilyl)propyl methacrylate (TPM). 3. Silica clusters are etched out via treatment with hydrofluoric acid. Electron micrographs of (b) silica clusters, (c) silica-TPM patchy particles, and (d) multicavity particles. (e) Confocal fluorescent images of fluorescently labeled multicavity particles. Scale bars, 1  $\mu\text{m}$ .

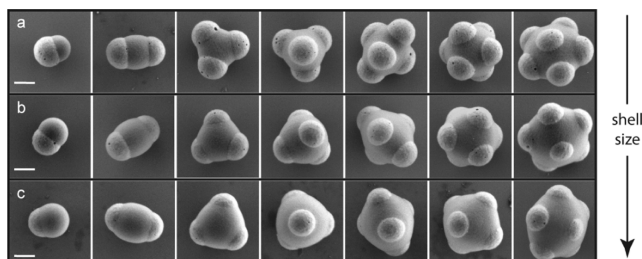
shape complementarity, should facilitate the assembly of a wide spectrum of colloidal materials.

We employed a template-based strategy (Figure 1a) to fabricate the multicavity particles, starting with the assembly of clusters of silica spheres as the sacrificial template through an emulsion–encapsulation process.<sup>22,23</sup> Specifically, silica spheres ( $d = 1.7$  or  $0.67 \mu\text{m}$ ) are first coated with octa-decyltrimethoxysilane (OTMOS) and dispersed in hexanes. The hexane dispersion is then emulsified into water containing Pluronic F108 (1% w/w) as a surfactant. After slow evaporation of hexanes, “minimal moment”<sup>22</sup> clusters are obtained (Figures 1b) with reproducible symmetries for clusters containing the same number of spheres.

In the next step, template filling, we partially encapsulate the silica clusters with an organo-silica hybrid shell. The shell is made of TPM in two steps: silane condensation (nucleation) and free radical polymerization (solidification). First, TPM is added to an aqueous suspension of clusters (containing Pluronic F108, pH = 9). Under basic conditions, the trimethoxysilane groups hydrolyze to give water-soluble silanols that rapidly condense, leading to a three-dimensional branched network. When the network grows and reaches critical solubility in water, it phase separates in the form of oil droplets. The oil preferentially condenses near the contact points between particles in the clusters, resulting in the

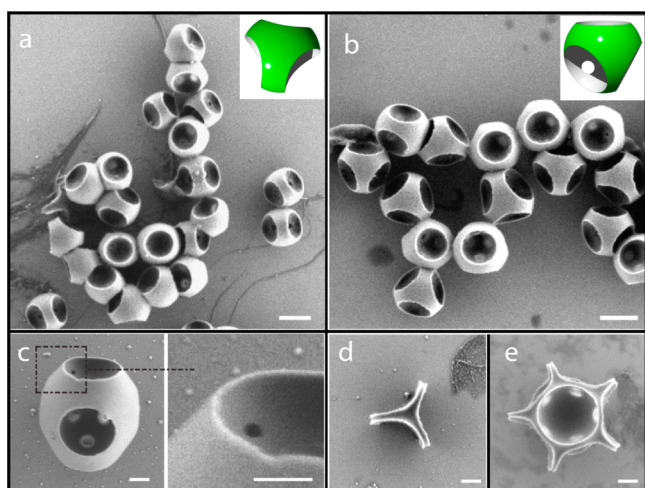
encapsulation of the clusters, proceeding from the center outward with the cluster extremities protruding as patches (Movie S1). After complete TPM condensation, an acrylate derivative of the fluorescent dye nitro-2,1,3-benzoxadiazol (NBD) and an oil-soluble initiator, azobis(isobutyronitrile) (AIBN), are added sequentially to the reaction mixture and allowed to gradually diffuse into the oil shell. Upon heating to 80 °C, AIBN decomposes and initializes a free radical polymerization of the methacrylate groups of the silane oligomers, solidifying the shell containing the NBD dye affording the desired biphasic patchy particles (Figure 1c).

The shell size of the patchy particle can be readily controlled by adjusting the TPM concentration, surfactant concentration, or reaction time. The higher the concentration of TPM, the larger the shells are. More surfactant results in smaller shells. This can be attributed to the fact that surfactant induces secondary nucleation producing small TPM particles and thus consuming TPM. Figure 2 shows SEM images of particles with different shell sizes synthesized under identical conditions but for the F108 concentration. Finally, reducing the hydrolysis time reduces the shell size. As shown in Figure S1 and Movie S1, the polymerizable oil droplets nucleate and slowly grow from the cluster centers. This slow growth allows us to freeze the particle configuration at any time by initializing the radical polymerization.



**Figure 2. Biphasic patchy particle shell size control.** Electron micrographs of silica patchy particles with TPM shell. The size of the shell can be varied by changing surfactant concentration. The weight percentage of F108 used during patchy particle fabrication is (a) 0.2%, (b) 0.1%, and (c) 0.05%. Scale bars, 500 nm.

The biphasic patchy particles are treated with an aqueous 4% hydrofluoric acid (HF) solution to remove the silica cluster templates. The TPM shell of the patchy particles is composed of two orthogonal cross-linked networks: carbon–carbon (C–C) linkages from the acrylates, and silicon–oxygen (Si–O) linkages from the silanes. HF breaks the Si–O bond leaving the C–C network intact. As a result, the shell undergoes a homogeneous shrinkage (14%) from its original size. Nevertheless, the original conformation is preserved. The silica cluster is fully etched away generating multiple spherical cavities with smooth inner surfaces (Figure 3c). The geometry of the cavities



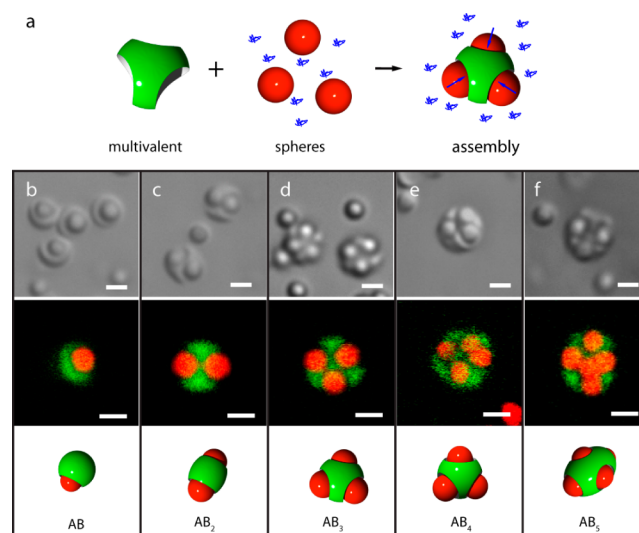
**Figure 3. Multicavity particles.** Electron micrographs of purified (a) three-cavity particles and (b) four-cavity particles. (c) (left) Particle with seven cavities and (right) high magnification of the cavity showing the smooth concave surface. Particles with (d) three and (e) seven shallow cavities obtained from patchy particles with small shell sizes. Scale bars, 500 nm.

is translated from the originally assembled templates, displaying well-defined three-dimensional symmetries, from spherical ( $n = 1$ ) to pentagonal bipyramidal geometries ( $n = 7$ ) (Figure 1d, Movie S2). Figure 1e shows the confocal fluorescent images of the multicavity particles, demonstrating that the dye molecule survives the etching treatment.

Particles containing one or more cavities are obtained as a mixture after the etching process. We can separate them using density gradient centrifugation. Figure 3a shows an SEM image of purified three-cavity particles, and Figure 3b, an SEM image of the four-cavity particles. All particles with the same number of cavities have identical size and symmetry.

We can control the shallowness and the size of the cavities. Etching patchy particles with a small shell results in hollow particles with a shallow cavity. Figure 3d and 3e show a three-cavity particle and a seven-cavity particle with shallow cavities. The diameter of the cavities is determined by the diameter of the silica spheres that constitute the cluster template. For example, particles with a cavity diameter of  $1.4 \mu\text{m}$  (Figures 1d, 3c–e) and  $0.57 \mu\text{m}$  (Figures 3a–b, S2) are obtained starting from  $1.7$  and  $0.67 \mu\text{m}$  silica spheres, respectively.

With the multicavity particles at hand, we investigate the binding of these “lock” particles to multiple complementary spheres (keys) via depletion interaction. Particles with relatively large and deep cavities ( $d = 1.4 \mu\text{m}$ , Figure 1d) are used as the “locks,” and poly(styrene) (PS) spheres, poly(methyl acrylate) spheres, or silica spheres as are used as keys ( $d = 1.0 \mu\text{m}$ ; for size selection, see Supporting Information). Poly(ethylene oxide) (PEO) ( $M_w = 600\,000$ ) is added as a depletant to an aqueous suspension containing both the locks and keys to induce the depletion interaction (Figure 4a). The depletion



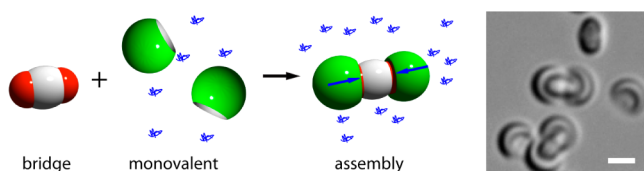
**Figure 4. Three-dimensional lock and key assemblies.** (a) Schematic illustration showing a trivalent particle with three assembled spheres using depletion interaction. The depletant (blue coil) causes osmotic pressure (arrows) between adjacent colloids, which is maximized when a sphere assembles into a cavity. (b–f) Bright field micrographs (top panel), confocal micrographs (middle panel), and cartoons (bottom panel) showing multivalent lock particles with (b) one, (c) two, (d) three, (e) four, and (f) five cavities binding to red fluorescent spheres stoichiometrically, forming  $AB$ ,  $AB_2$ ,  $AB_3$ ,  $AB_4$ , and  $AB_5$  colloidal molecules, respectively. Scale bar,  $1 \mu\text{m}$ .

driven sphere–cavity binding is favored because it maximizes the free volume of the PEO and thus results in a stronger attraction compared to any other nonspecific lock and key contact (e.g., sphere–sphere, sphere–matrix). At the  $0.5 \text{ g/L}$  PEO concentration with a 5-fold excess of keys to lock cavities, approximately 60% of the overall cavities are filled after overnight assembly independent of the chemical composition and the surface chemistry of the spheres.

We characterize the assembled structures using both bright-field and fluorescent microscopies. We use red fluorescently labeled PS spheres and assemble them into the green fluorescently labeled multicavity particles (Figures 4b–f, S3, Movie S3). Monovalent lock particles can bind to PS spheres to form  $AB$  type colloidal molecules (Figure 4b). Divalent lock

particles bind with two spheres in a linear configuration (Figure 4c). Triangular, tetrahedral, and trigonal dipyramidal arrangements of red spheres are likewise seen to bind with trivalent, tetravalent, and pentavalent lock particles, resulting in AB<sub>3</sub>, AB<sub>4</sub>, and AB<sub>5</sub> type molecules (Figure 4d–4f). Each cavity in the multivalent particle acts as a binding pocket that accepts a complementary sphere. With the predefined cavity position, three-dimensional interaction is achieved based on complementary shapes.

A prerequisite for the formation of higher ordered assembled structures is that the cavities on different particles can be linked together. We mixed monovalent particles with ellipsoid particles (two-patch particle made from 800 nm silica spheres) in the presence of a depletant. The ellipsoid particle acts as a bridge binding to two monovalent particles in a linear configuration (Figure 5). This demonstrates the potential to employ the directionality embedded in the multicavity particle for the construction of extended colloidal architectures.



**Figure 5.** Two monovalent particles bridged via the assembly with an ellipsoid particle. Scale bar, 1  $\mu\text{m}$ .

The multivalent lock and key binding is reversible and flexible. By lowering the PEO concentration and thereby the binding energy, the majority of the hollow particle–sphere assemblies disassemble and participate in random Brownian motion without any directional assembly. Additionally, due to the lack of chemical bonding, the spheres are rotating freely within the cavities (e.g., not locked into one conformation) (Movie S3).

In conclusion, we have fabricated particles with multiple cavities using silica clusters as sacrificial templates and the corresponding patchy particle as an intermediate. The organosilane shell made from TPM partially encapsulates the cluster to copy the configuration and remains intact during the etching process, affording the final multicavity particles. The ability to control the geometrical complexity of our hollow particles leads to a concurrent capacity to exhibit multivalent directional depletion interactions based on shape complementarity. This provides a straightforward methodology to incorporate materials with various chemical compositions and surface chemistries into well-defined “colloidal molecules”. With intrinsic flexibility and reversibility of the binding, complex colloidal architectures such as kagome or diamond lattices should be accessible by mixing trivalent or tetravalent particles with ellipsoid particles.

## ■ ASSOCIATED CONTENT

### 📄 Supporting Information

Experimental procedures, supplementary figures, and movies. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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### Notes

The authors declare no competing financial interest.

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