Polyhedra are ubiquitous in chemistry, biology, mathematics and other disciplines. Coordination-driven self-assembly has created molecules mimicking Platonic, Archimedean and even Goldberg polyhedra, however, nesting multiple polyhedra in one cluster is challenging, not only for synthesis but also for determining the alignment of the polyhedra. Here, we synthesize a nested Ag\textsubscript{90} nanocluster under solvothermal condition. This pseudo-Th\textsubscript{h} symmetric Ag\textsubscript{90} ball contains three concentric Ag polyhedra with apparently incompatible symmetry. Specifically, the inner (Ag\textsubscript{6}) and middle (Ag\textsubscript{24}) shells are octahedral (Oh), an octahedron (a Platonic solid with six 3.3.3.3 vertices) and a truncated octahedron (an Archimedean solid with twenty-four 4.6.6 vertices), whereas the outer (Ag\textsubscript{60}) shell is icosahedral (I\textsubscript{h}), a rhombicosidodecahedron (an Archimedean solid with sixty 3.4.5.4 vertices). The Ag\textsubscript{90} nanocluster solves the apparent incompatibility with the most symmetric arrangement of 2- and 3-fold rotational axes, similar to the arrangement in the model called Kepler’s Kosmos, devised by the mathematician John Conway.
Encouraged by masterpieces of self-assembly in biology\textsuperscript{1–5}, some seminal metal clusters\textsuperscript{6} of nanometer size have been assembled from simple components\textsuperscript{7–12}, such as Al\textsubscript{17}\textsuperscript{13}, Gd\textsubscript{140}\textsuperscript{14}, Pd\textsubscript{145}\textsuperscript{15}, Ag\textsubscript{874}\textsuperscript{16}, and Au\textsubscript{1346}. Among families of metal clusters, silver nanoclusters benefit from the exceptional versatility of silver(I) atoms, which have flexible coordination preferences, a tendency to form argentophilic interactions and a susceptibility to reduction, all properties enriching the number of synthetic routes for single polyhedral silver nanoclusters. Silver(I) nanoclusters can form with the assistance of surface ligands, inner anion templates and argentophilic interactions. Nonetheless, most silver nanoclusters lack typical polyhedral features. Exceptionally, in 2017, we synthesized a buckyball-like Goldberg cage with 180 Ag atoms\textsuperscript{25}.

Even more complex is a nested silver(I) nanocluster with two or more chemically bound metallic shells. Examples include Ag\textsubscript{96} (Ag\textsubscript{84}⊂Ag\textsubscript{12})\textsuperscript{26}, Ag\textsubscript{96} (Ag\textsubscript{82}⊂Ag\textsubscript{14})\textsuperscript{27}, Ag\textsubscript{62} (Ag\textsubscript{14}⊂Ag\textsubscript{14})\textsuperscript{28}, and Ag\textsubscript{78} (Ag\textsubscript{18}⊂Ag\textsubscript{60})\textsuperscript{29}, but even in these cases, most of the shells lack typical polyhedral features, and the number of silver shells is just two. We assembled the first three-shell Ag\textsubscript{93} silver nanocluster with a central Ag atom in an Ag\textsubscript{48} rhombicuboctahedron in an Ag\textsubscript{48} octahedral Goldberg 2,0 polyhedron\textsuperscript{30}. Although there has been progress, the synthetic challenges in making single polyhedral and nested polyhedral silver nanoclusters remain due to the difficulty of precisely shaping silver polygons and obtaining polyhedral shells with compatible symmetry. Here, we report the synthesis and characterization of nested Ag\textsubscript{90} nanoclusters which show pseudo-T\textsubscript{3} symmetry and contain three concentric silver polyhedra with apparently incompatible symmetry. The nested silver shells can be expressed as Ag\textsubscript{6}⊂Ag\textsubscript{24}⊂Ag\textsubscript{90} and belong to octahedron, truncated octahedron, and rhombicosidodecahedron, respectively. The Ag\textsubscript{90} nanocluster solves the apparent incompatibility with the most symmetric arrangement of two- and threefold rotational axes.

Results

Structures of SD/Ag\textsubscript{90}a and SD/Ag\textsubscript{90}b. With a combination of anion-template and geometrical-polyhedron strategies\textsuperscript{31–37} and with careful choice of organic ligands (\textit{BuSH} and PhPO\textsubscript{4}H\textsubscript{2}) and anion templates (S\textsuperscript{2–} and PO\textsubscript{4}\textsuperscript{3–}), we one-pot synthesized Ag\textsubscript{90} nanoclusters under the solvothermal condition as dark brown or red rhombic crystals, depending on the polymorphs. They are stable under ambient conditions because the bulk sample of them can keep the color and morphology unchanged for at least one month. The PO\textsubscript{4}\textsuperscript{3–} ion was considered as anion-template mainly due to its high negative charge and T\textsubscript{d} symmetry. The former feature can aggregate more Ag\textsuperscript{+} ions to form high-nuclearity cluster through electrostatic attraction, whereas the latter can shape cluster with a T-related symmetry. The Ag\textsubscript{90} nanoclusters can be crystallized into a monoclinic P\textsubscript{2}1/a or triclinic P\textsubscript{1} phases dictated by the silver salts used (Fig. 1), hereafter denoted as SD/Ag\textsubscript{90}a and SD/Ag\textsubscript{90}b, respectively. Although the different anions, PhCOO\textsuperscript{−} and CH\textsubscript{3}SO\textsubscript{3}\textsuperscript{−}, did not participate in the final structures of the Ag\textsubscript{90} clusters, they may have influenced the crystalization process through supramolecular interactions such as hydrogen bonds, which causes the formation of the ultimate crystalline phases. Other common silver salts, such as AgBF\textsubscript{4}, CF\textsubscript{3}COOAg, CF\textsubscript{3}SO\textsubscript{3}Ag, and AgNO\textsubscript{3}, were tried in the above synthesis experiments, but none produced desired clusters. A series of characterization techniques such as single-crystal X-ray crystallography, infrared spectroscopy, \textsuperscript{31}P nuclear magnetic resonance, ultraviolet-visible absorption spectroscopy, fluorescence spectroscopy, and thermogravimetric analysis were used on these two nests (Supplementary Figs. 1–5, 13–17 and Supplementary Tables 1–3). The electrospray ionization mass spectrometry (ESI-MS) of SD/Ag\textsubscript{90}a dissolved in CH\textsubscript{2}Cl\textsubscript{2} or CH\textsubscript{3}OH did not give useful data, which indicates that either (i) SD/Ag\textsubscript{90}a is fragmented during the ionization process or (ii) it is neutral and is hard to ionize under mass spectrometer conditions—even when we added CsOAc to aid in ionization\textsuperscript{38}.

As deduced from crystallography, SD/Ag\textsubscript{90}a (Fig. 2a) and SD/Ag\textsubscript{90}b (Supplementary Fig. 6a) have the same molecular structure of SD/Ag\textsubscript{90}a incorporating Van der Waals surfaces. Hydrogen atoms are removed for clarity. Color legend: Ag, purple; P, brown; S, yellow; O, red; C, gray. b The ball-and-stick model of the triply nested polyhedral silver skeleton, viewed down an axis through the front silver 5-gon. The three different shells are individually colored. c The icosahedral Ag\textsubscript{60} rhombicosidodecahedron. d The octahedral Ag\textsubscript{24} truncated octahedron. e The octahedral Ag\textsubscript{60} octahedron. f The interactions between eight PO\textsubscript{4}\textsuperscript{3–} and three different shells. g The detailed coordination of PO\textsubscript{4}\textsuperscript{3–} towards different silver polygons in three different shells. All PO\textsubscript{4}\textsuperscript{3–} ions are shown as yellow tetrahedra. h Six µ\textsubscript{4}– S\textsuperscript{2–} ions intercalate the aperture between Ag\textsubscript{24} and Ag\textsubscript{60} shells of SD/Ag\textsubscript{90}a by linking two 4-gons up and down from these shells, respectively.

Fig. 1 Synthetic routes for SD/Ag\textsubscript{90}a and SD/Ag\textsubscript{90}b. The photos of crystals were taken in the ambient environment with a digital camera. X represents the counter-ions in the silver salts (AgX) used in the syntheses. DMF = N,N-dimethylformamide. Scale bar: 0.3 mm.
structure and composition of [(PO₄)₈@Ag₉₀S₆(tBuS)₂₄(PhPO₃)₁₂(PhPO₃H)₆], but they crystallize into different space groups (Supplementary Table 1) due to different cluster packing in their unit cells (Supplementary Figs. 7 and 8). The straightforward single-crystal X-ray diffraction (SCXRD) of crystals at 100 K unambiguously established ball-shaped structures for the Ag 90 nanoclusters (Fig. 2b–e; Supplementary Figs. 6b–e, 9, 10). Due to the similarity of their molecular structures, we take SD/Ag₉₀a as representative for discussions in detail below.

SD/Ag₉₀a crystallized into the monoclinic P2₁/n space group and conformed to pseudo-Th symmetry. SD/Ag₉₀a is a neutral cluster with all Ag(I) atoms in 3- or 4-coordination with S and/or O atoms. The all-silver framework (Fig. 2b) is composed of three concentric nested polyhedra, an outer Ag₆₀ rhombicosidodecahedron with 60 3.4.5.4 vertices (Fig. 2c), a middle Ag₂₄ truncated octahedron with 24 4.6.6 vertices (Fig. 2d), and an inner Ag₆ octahedron with 6 3.3.3.3 vertices (Fig. 2e), where the numbers 5, 4, and 3 represent faces around that vertex, respectively, 5-gons, 4-gons, and 3-gons. Of note, the outer Ag₆₀ shell is geometrically reminiscent of the third shell (Pd₆₀) in Dahl’s Pd₄₄₅ cluster¹⁵. All vertices on these three polyhedra are Ag(I) atoms, and all edges are built from the connection of adjacent two Ag atoms. The Ag–Ag edge lengths in outer, middle, and inner shells range from 2.96 to 4.03, 3.02 to 3.48, and 3.51–3.61 Å, respectively (Supplementary Fig. 11 and Supplementary Table 3). Some of these Ag–Ag edge lengths, shorter than 3.44 Å, twice the Van der Waals radius of silver(I) ion, can be deemed as argentophilic interactions that contribute to the stability of the silver shells. Of note, the long Ag–Ag edges in the Ag₆ octahedron also rule out a subvalent nature, which usually produces short Ag–Ag distances approximating to 2.88 Å³⁹. By measuring distances between inversion-related pairs of Ag atoms in the same shell, the diameters of outer, middle and inner shells are determined to be 1.5, 1.0, and 0.5 nm, respectively.

Each μ₁₂κ³κ³κ³κ³PO₄³⁻ ion (as anion-template) penetrates the hexagonal windows of the Ag₂₄ shell to connect all three silver shells (Ag-O: 2.3–2.6 Å) by linking two silver 3-gons of the Ag₆₀ and Ag₆₀ shells and one 6-gon of the Ag₂₄ shell (Fig. 2f, g). Six μ₈⁻S²⁻ ions from in situ decomposition of tBuSH intercalate the aperture between Ag₂₄ and Ag₆₀ shells (Ag-S: 2.43–2.89 Å) by linking two 4-gons up and down from these shells, respectively (Fig. 2h)²⁸. Based on the above analysis, we found that the tetrahedral PO₄³⁻ ion has a special role in shaping silver 3-gons and 6-gons, essential elements to construct the rhombicosidodecahedron and the truncated octahedron, respectively. As for the spherical S²⁻ ion, it assists in fabricating the silver 4-gon, an essential element for both the rhombicosidodecahedron and the truncated octahedron. Both inorganic anions act not only as templates to shape the silver polyhedra by defining the essential...
polygon elements but also function as glue to consolidate the overall nested silver shells.

The ligand coverage on the surface of the outer Ag₆₀ shell is polygon selective with 24 tBuS− and 6 PhPO₃H− on thirty 4-gons and 12 PhPO₃²− on twelve 5-gons. There are no ligands capping the twenty 3-gons. The PhPO₃H₂ ligand exhibits two kinds of deprotonated forms, PhPO₃²− and PhPO₃H−, that respectively coordinate with twelve 5-gons (μ₄-κ²:κ¹) and six 4-gons (μ₄-κ²:κ²) on the surface of the Ag₆₀ shell (Ag-O: 2.2–2.6 Å). The ³¹P NMR (nuclear magnetic resonance) of the digestion solution of SD/Ag⁹₀a shows two sharp peaks with chemical shifts at δ = −1.07 and 15.62 ppm (Supplementary Fig. 2), corresponding to H₃PO₄ and PhPO ³H₂, respectively, which clearly verify the existence of two different P-containing chemicals in SD/Ag⁹₀a.

From the ligation modes of each coordinative component, we suggest that all of them play roles to shape different silver polygons, paving the way for further construction of polyhedral silver nanoclusters. The overall structure is reinforced by a combination of argentophilic interactions (<3.44 Å) and the scaffolding provided by all other coordination bonds. The remarkable structure of SD/Ag⁹₀a has not been previously observed in the family of silver nanoclusters.

**Alignment of shells with compatible point-group symmetry.**

We now ask about the alignment of the icosahedral and octahedral cages in the SD/Ag⁹₀a nest. For the dodecahedron and its dual (the icosahedron), both Platonic solids with icosahedral (Ih) symmetry and thus “compatible”, nesting may be based on alignment of all of the five-, three- and twofold axes of rotational symmetry (Fig. 3a; Supplementary Table 4). The same full alignment could obtain for nests of any icosahedral structures, including the six icosahedral Archimedean solids and an infinity of other icosahedral structures. Likewise, nesting of octahedral shells like the cube and its dual (the octahedron)—both Platonic solids—within silver nanoclusters has been predicted.
tetrahedron and its self-dual (the tetrahedron) (Fig. 3c) with each other may be based on alignment of all rotational axes (Supplementary Table 4). Indeed, the Ag_{73} cited above is just such a symmetry-compatible nesting of octahedral silver cages.

Alignment of shells with incompatible point-group symmetry. Although it might be assumed that only cages with compatible symmetry (e.g., icosahedral with icosahedral) could be nested, for the Zometool toy the mathematician John Conway created a model called “Kepler’s Kosmos”, a model that aligns the five Platonic solids, the two with icosahedral symmetry, the two with octahedral, and the one with tetrahedral. As its name suggests, the inspiration for this model dates back to Johannes Kepler. In 1596, in his Mysterium Cosmographicum (The Secret of the Universe), Kepler hypothesized that the orbits of the six known planets corresponded with six spheres, five circumscribing the five Platonic solids and one inscribing the smallest. To test his hypothesis, Kepler became mathematical assistant to Tycho Brahe in 1600 and gained access to more than 30 years of astronomical observations. By 1605, Kepler had shown that the orbit of Mars was an ellipse, culminating by 1619 with his discovery of the three laws of planetary motion and subsequently Isaac Newton’s discovery of the law of universal gravity.

Kepler’s Kosmos provides one possible answer to the question of how to align icosahedral polyhedra with fivefold rotational axes but no fourfold, octahedral polyhedra with fourfold axes but no fivefold, and tetrahedral polyhedra with neither. Conway’s
arrangement (Fig. 4a; Supplementary Fig. 12a and Supplementary Table 4) has these properties: (i) None of the six fivefold axes of the dodecahedron (or icosahedron) is aligned with any rotational axis of an octahedral or tetrahedral polyhedron. (ii) Four of the ten threefold axes of the dodecahedron (or icosahedron) are aligned with all four threefold axes of the cube (or octahedron) and all four threefold axes of the tetrahedron (Fig. 4b–e). (iii) Three of the fifteen twofold axes of the dodecahedron (or icosahedron) are aligned with all three (orthogonal) fourfold axes of the cube (or octahedron) and all three (orthogonal) twofold axes of the tetrahedron (Fig. 4f–i). This quintuple nest itself has tetrahedral (T_d) symmetry.

However, other alignments are possible. Here, we devise an alternative alignment with three different combinations of four- and twofold axes to produce a nest with just three different, orthogonal twofold axes (Fig. 5; Supplementary Fig. 12b, Supplementary Table 4, and Supplementary Movie 1), producing a quintuple nest with lower (D_2) symmetry. Of course, it is also possible to align none of the rotational axes, producing a quintuple nest with trivial (C_1) symmetry.

Alignment of shells in SD/Ag90a. Given different symmetric arrangements of the three shells—as in the Kepler’s Kosmos with point-group T_d (Fig. 4), alignment of only three different orthogonal twofold axes with point-group D_2 (Fig. 5) and no alignment of rotational axes (thus C_1)—we ask how the shells in SD/Ag90a align. The icosahedral outer shell of SD/Ag90a has fivefold axes, but these are absent in the octahedral middle and inner shells (Fig. 2b). The octahedral inner and middle shells compatibly align all of their four-, three- and twofold axes, as in Fig. 3b. The icosahedral outer shell aligns four of its threefold axes with all four of the threefold axes of the octahedral shells (Fig. 6a) and three of its twofold axes with all three fourfold axes of the octahedral shells (Fig. 6b). Of note, the interstitial anions of S_2^- and PO_4^{3-} also have important influences on aligning the three shells. Specifically, the threefold axes of the Ag_{60}, Ag_{24}, and Ag_{60} shells pass through the PO_4^{3-} ions, and the twofold axis of Ag_{60} shell and fourfold axis of Ag_{24} shell pass through the S_2^- ions, thus dictating the alignment of three different shells in the unique fashion discussed above. The alignment of these approximate polyhedra is nearly as good as in the same nest with regular polyhedra (Fig. 6c, d). Thus, the arrangement of the icosahedral and octahedral shells in the Ag_{90} triple nest is the same as in Kepler’s Kosmos (Fig. 4).

However, without a tetrahedral shell, SD/Ag90a is a subset of Kepler’s Kosmos, with just I_h (3.4.5.4) and O_h (4.6.6 and 3.3.3.3) shells. As both I_h and O_h structures have inversion symmetry, their combination in SD/Ag90a also has inversion symmetry. Thus, the regular version of SD/Ag90a (Fig. 6c, d), with four threefold axes, three twofold axes, mirrors, inversion, and a symmetry order of 24, has T_i, symmetry (Supplementary Table 4).

Optical properties of SD/Ag90a. The solid-state ultraviolet–visible (UV/Vis) absorption spectra of SD/Ag90a and [‘BuSAg]_n were measured at room temperature. As shown in Fig. 7a, SD/Ag90a exhibits a wide absorption range spanning UV and Vis regions with an absorption maximum at 419 nm. Compared with the absorption of [‘BuSAg]_n at 280 nm, the absorption edge is
We further studied the photocurrent responses of SD/Ag90a and [BuSAGa] driven by visible-light in a typical three-electrode system (ITO glass as the working electrode, platinum wire as the assisting electrode and Ag/AgCl as the reference electrode) and keeping the bias voltage at 0.6 V. Upon on–off cycling irradiation with LED light (λ = 420 nm; 50 W; intervals of 10 s), clear photocurrent responses were observed for SD/Ag90a and [BuSAGa] (Fig. 7b). The photocurrent density of SD/Ag90a (0.9 μA cm⁻²) was five times larger than that of [BuSAGa] (0.17 μA cm⁻²), indicating that SD/Ag90a has better generation and separation efficiency of photoinduced electrons/holes pairs in ITO electrodes. The generation of photocurrent may involve photoinduced charge migration from S 3p to the Ag 5s orbits.

The solid state emission spectra of SD/Ag90a were recorded as a function of temperature from 293 to 93 K with 40 K as an interval, showing luminescence thermochromic behavior (Fig. 8). The luminescence of SD/Ag90a originates from the ligand-to-metal charge transfer transition with a charge transfer from S 3p to Ag 5s orbitals and/or mixed with a cluster-centered transition related to Ag–Ag interactions. SD/Ag90a shows gradually blue-shifted emissions from 700 to 684 nm (λₘₐₓ = 468 nm) upon cooling, possibly related to enhanced molecular rigidity at lower temperatures. During the cooling process, the emission intensity shows a nearly tenfold increase from 293 to 93 K, which is attributed to reduction of the nonradiative decay at low temperature.

Discussion
We have successfully synthesized an Ag₉₀ nanocluster with overall pseudo-Tₐ symmetry. This silver nanocluster is divided into three shells as Ag₈₆Ag₄Ag₀ from inner to outer. The Ag₈₆ inner shell is an octahedron (a Platonic solid with 6 3,3,3,3 vertices), the Ag₄₄ middle shell is a truncated octahedron (an Archimedean solid with 24 4,6,6 vertices), and both have octahedral (O₈) symmetry. However, the Ag₀ outer shell is a rhombicosidodecahedron (an Archimedean solid with 60 3,4,5,4 vertices and icosahedral (I₉) symmetry). The SD/Ag90a nanocluster solves the apparent incompatibility among their symmetry groups with the most symmetric arrangement of two- and threefold axes. Creation of a nest with all three of the polyhedral symmetries, icosahedral, octahedral and tetrahedral—and resembling Kepler’s Kosmos even more closely—remains an exciting challenge.

Methods
Syntheses of SD/Ag90a and SD/Ag90b
[11] SAD/Ag90a (9.9 mg, 0.05 mmol), PhCOOAg (11.5 mg, 0.05 mmol), Na₃PO₄·12H₂O (5 mg, 0.013 mmol), and PhPO₄H₂ (4.7 mg, 0.03 mmol) were dissolved in 6.5 ml MeOH/MeCN/DMF (v/v/v = 6:6:6). The resulting suspension was sealed and heated at 65 °C for 2000 min. After cooling to room temperature, dark brown crystals of SD/Ag90a were formed (yield: 30%). Combustion elementary analysis calculated (experimental) for SD/Ag90a: C₃₀₃H₁₇₂Ag₉₀O₈₆P₂₆S₃₀: C, 15.69 (15.71%); H, 2.01 (1.99%). The solid state emission spectra of SD/Ag90a and [BuSAGa] were recorded as a function of temperature from 293 to 93 K with 40 K as an interval.

![Fig. 7](image_url) The UV–Vis spectra and photocurrent responses of SD/Ag90a and [BuSAGa]. a The normalized UV–Vis spectra of SD/Ag90a and [BuSAGa] precursor in the solid state. b Compared photocurrent responses of blank, SD/Ag90a, and [BuSAGa], ITO electrodes in a 0.2 M Na₂SO₄ aqueous solution under repetitive irradiation.

![Fig. 8](image_url) Varied-temperature luminescence spectra of SD/Ag90a from 293 to 923 K with 40 K as an interval. Insets show the photographs of a sample of SD/Ag90a under a hand-held UV lamp (365 nm) at 293 and 77 K.

significantly red-shifted in SD/Ag90a, which should be caused by the ligand-to-metal charge transfer (LMCT) or/and cluster-centered (CC) transitions. Based on the Kubelka–Munk function of (a(hυ)² = k(hυ – Eₜ)) (Eₜ is the band gap (eV), h is Planck’s constant (Js), v is the light frequency (s⁻¹), k is the absorption constant, and a is the absorption coefficient), the band gaps of SD/Ag90a and [BuSAGa]ₙ precursor were determined as 0.69 and 2.34 eV, respectively (Supplementary Fig. 3), which indicates that the aggregation of multiple silver atoms into a cluster structure has an important influence on the HOMO–LUMO gap.

![Figure](image_url) The normalized UV–Vis spectra of SD/Ag90a and [BuSAGa] precursor in the solid state. Based on the Kubelka–Munk function of (a(hυ)² = k(hυ – Eₜ)) (Eₜ is the band gap (eV), h is Planck’s constant (Js), v is the light frequency (s⁻¹), k is the absorption constant, and a is the absorption coefficient), the band gaps of SD/Ag90a and [BuSAGa]ₙ precursor were determined as 0.69 and 2.34 eV, respectively (Supplementary Fig. 3), which indicates that the aggregation of multiple silver atoms into a cluster structure has an important influence on the HOMO–LUMO gap.
References

1. Bale, J. B. et al. Accurate design of megadalton-scale two-component icoshedral protein complexes. Science 353, 389–394 (2016).
2. He, Y. et al. Hierarchical self-assembly of DNA into symmetric supramolecular polyhedra. Nature 452, 198–201 (2008).
3. Douglas, S. M. et al. Self-assembly of DNA into nanoscale three-dimensional shapes. Nature 459, 414–418 (2009).
4. Laub, D. M. et al. Solving the structure of human H ferritin by genetically engineering intermolecular crystal contacts. Nature 349, 541–544 (1991).
5. Caspar, D. L. D. & Klug, A. Physical principles in construction of regular viruses. Cold Spring Harb. Symp. Quant. Biol. 27, 1–24 (1962).
6. Fujita, D. et al. Self-assembly of tetrahedral Goldberg polyhedra from 144 small components. Nature 540, 563–566 (2016).
7. Shi, J. F., Virovacz, A. V. & Scher, M. Synthesis of inorganic fullerene-like molecules. Science 300, 781–783 (2003).
8. Moses, M. J., Fettinger, J. C. & Eichhorn, B. W. Interpenetrating As20 fullerene nanowheels. Nature 452, 198–201 (2008).
9. He, Y. et al. Hierarchical self-assembly of DNA into symmetric supramolecular polyhedra. Nature 452, 198–201 (2008).
10. Li, S. et al. Atom-scale modification of silver(I) thiolate cluster by shell ligand substitution: a new approach to generation of cluster functionality and chirality. J. Am. Chem. Soc. 130, 594–597 (2008).
11. Wang, Z. et al. Trapping an octahedral Ag56 nanowheel. Nat. Commun. 9, 2048 (2018).
12. Liu, X., Yang, H., Zheng, N. & Zheng, L. Bromide-induced formation of a highly symmetric silver thiolate cluster containing 36 silver atoms from an infinite polymeric silver thiolate. Eur. J. Inorg. Chem. 2010, 2084–2087 (2010).
13. Bootharaju, M. S. et al. A new class of atomically precise, hydride-rich silver nanoclusters co-protected by phosphines. J. Am. Chem. Soc. 138, 13770–13773 (2016).
14. Chen, T., Yao, Q., Nasaruddin, R. R. & Xie, J. Electrospray ionization mass spectrometry: a powerful platform for noble-metal nanocluster analysis. Angew. Chem. Int. Ed. 1346 (2008).
