

Cite this: *Chem. Sci.*, 2022, 13, 11110

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# Snapshots of key intermediates unveiling the growth from silver ions to Ag<sub>70</sub> nanoclusters†

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Nanoclusters (NCs) are considered as initial states of condensed matter, and unveiling their formation mechanism is of great importance for directional synthesis of nanomaterials. Here, we initiate the reaction of Ag(I) ions under weak reducing conditions. The prolonged reaction period provides a unique opportunity for revealing the five stages of the growth mechanism of 20-electron superatomic Ag<sub>70</sub> NCs by a time-dependent mass technique, that is, aggregate (I) → reduction (II) → decomposition and recombination (III) → fusion (IV) → surface recombination and motif enrichment (V), which is different from the formation process applicable to the gold clusters. More importantly, the key intermediates, Ag<sub>14</sub> without free electrons (0e) in the first (stage I) and Ag<sub>24</sub> (4e) in the second (stage II), were crystallized and structurally resolved, and the later transformation rate towards Ag<sub>70</sub> was further controlled by modulating solvents for easy identification of more intermediates. In a word, we establish a reasonable path of gradual expansion in size and electrons from Ag(I) ions to medium-sized 20e Ag<sub>70</sub>. This work provides new insights into the formation and evolution of silver NCs, and unveils the corresponding optical properties along with the process.

Received 28th July 2022  
Accepted 26th August 2022

DOI: 10.1039/d2sc04204e

rsc.li/chemical-science

## Introduction

Atomically precise coinage metal (M = Au,<sup>1</sup> Ag,<sup>2</sup> Cu<sup>3</sup>) nanoclusters as the bridges between atoms and nanoparticles,<sup>4</sup> which provide a unique opportunity for gaining fundamental knowledge of nanoparticles, are a newly emerging hot topic in nanoscience. Their diverse aesthetic structures with discrete energy levels and extensive modification greatly promote their increasing attraction in the fields of chirality,<sup>5</sup> luminescence,<sup>6</sup> catalysis,<sup>7</sup> sensing,<sup>8</sup> and biomedicine.<sup>9</sup> Clear identification of the grand evolution of structures and properties from discrete atoms to the metallic state, and the effectively controlled synthesis of intermediates of large-sized metal NCs remain tough tasks.<sup>10</sup> Xie and co-workers investigated the formation mechanism and evolution process of atomically precise thiolate-stabilized Au and Ag NCs from simple metal-thiolate precursors by real-time electrospray ionization-mass spectrometry (ESI-MS).<sup>11</sup> For gold NCs,

the step-by-step formation process from Au(I)-SR monomers to oligomers to NCs has been revealed by using well-known model Au<sub>25</sub>.<sup>11ef</sup> Wang developed a facile approach to assemble different thiolate-stabilized Au<sub>25</sub> with eight valence electrons (8e) in high yield (~100%) on a large scale, starting from a preformed Au<sub>13</sub> (8e) crystalline material, showing that the formation of metal NCs can be achieved by forming stable metal cores and then enriching Au(I)-SR staples on the surface.<sup>12</sup> Generally, the most commonly used method for the preparation of “medium/large-sized” metal NCs (nucleus number more than 50) is the reduction of metal precursors with appropriate reducing agents (such as NaBH<sub>4</sub>, Ph<sub>2</sub>SiH<sub>2</sub>, and the borane tertbutylamine complex).<sup>13</sup> The reduction process (M(I) → M(0)) is basically completed within a few minutes and this quick reduction process makes it difficult to capture the intermediates in the single crystal form.<sup>11d-g</sup>

The structure and size of silver NCs are considered to be mainly related to the number of silver atoms in the intermediate products.<sup>11g</sup> So far, the detailed process from silver ions to NCs, including the reduction and nucleation process for metal NCs is still a black box. Recently, we reported a 20e Ag<sub>70</sub> nanocluster, [(NH<sub>2</sub>(CH<sub>3</sub>)<sub>2</sub>)[Ag<sub>70</sub>S<sub>4</sub>(S<sup>i</sup>Pr)<sub>24</sub>(CF<sub>3</sub>COO)<sub>20</sub>]],<sup>14</sup> using DMF as a reductant. The slow reduction process to Ag<sub>70</sub> in ten hours (Fig. 1) provides a platform to follow the growth process, capture intermediates and reveal the formation mechanism of the “medium-sized” silver NCs.

In this work, we carefully studied the formation of Ag<sub>70</sub> (ref. 14) by time-dependent UV-vis spectroscopy and ESI-MS. By controlling the synthesis conditions, we successfully

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† Electronic supplementary information (ESI) available: Fig. S1–S31 and Tables S1–S9 for experimental details, detailed crystallographic structures, DFT, UV, ESI-MS, and crystal data of nanoclusters. CCDC 2182448, 2182449, and 2182450. For ESI and crystallographic data in CIF or other electronic format see <https://doi.org/10.1039/d2sc04204e>

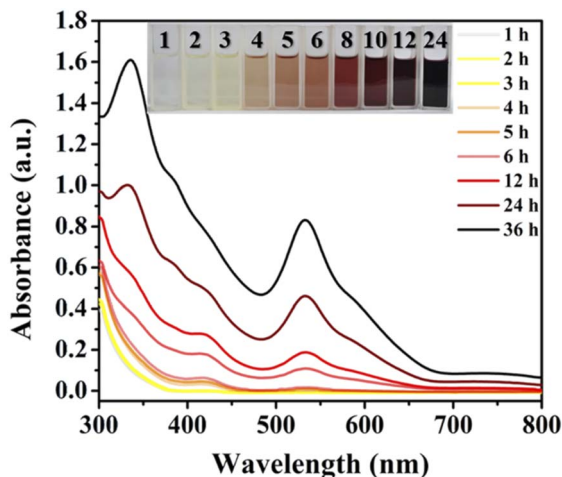


Fig. 1 Time-dependent UV-vis absorption spectra for tracking the reaction process. Experimental method: 9 mg  $\{Ag(S^iPr)_n\}$ , 22 mg  $CF_3COOAg$ , and 50  $\mu L$   $CF_3COOH$  in the solvent mixture (iPrOH : DMF = 3 : 1) at 80  $^{\circ}C$ . Inset: the colour of mother liquor after the solvothermal reaction at different times (1–24 h).

crystallized the key species  $Ag_{24}S(S^iPr)_8(CF_3COO)_{10}(DMF)_{10}$  (denoted as  $Ag_{24}$ ) with four valence electrons ( $4e$ ).  $Ag_{24}$  has two relatively independent delocalized centers  $Ag_6^{4+}$ , separated by an anion-template  $S^{2-}$ . Time-dependent ESI-MS and the mass difference fingerprint of isomorphism (MDFI) method unveil the transformation process from  $Ag(I)$  ions,  $4e$   $Ag_{24}$  to  $20e$   $Ag_{70}$ . Careful analysis based on the experimental data shows that  $Ag_{70}$  is not directly formed *via* DMF reduction from  $Ag(I)$  ions or pre-generated  $Ag(I)$ -S aggregates with a similar size, but generated through a cascade of reactions of the intermediates, including aggregation, reduction, decomposition, recombination, fusion, surface recombination and motif enrichment. The formation mechanism of the medium-sized silver NCs is instructive and meaningful in revealing the essence of the original state of metal nanoparticles.

## Results and discussion

### Tracking the growth process of $Ag_{70}$

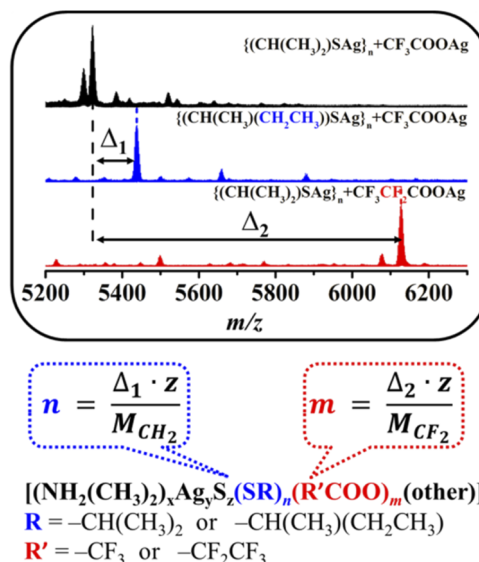
Identification of the intermediate species by the high-resolution ESI-MS technique during the reduction process is a straightforward and effective method to elucidate the growth mechanism of metallic NCs, which has been achieved in the synthesis of classic gold clusters.<sup>11a-f,12</sup> However, the complexity of the reaction system and the mutable inheritance of silver intermediate species hinder the in-depth study of Ag NCs. Little progress based on the structural evolution and size expansion of  $Ag^0$ -containing homosilver NCs is reported.<sup>11g</sup> Recently, it was found that the reaction solution of the superatomic Ag NC ( $Ag_{70}$ ) reported by our group has obvious color changes (from yellow to red (black), Fig. 1) at different times, and there may be intermediate products which are beneficial to explore the growth process of  $Ag_{70}$ .

A series of improved experiments were carried out to achieve our goal (Fig. S1–S5, see details in the ESI†). Using different

reaction times or conditions to control the reduction process, the color of the mother liquor is significantly different (Fig. 1), which indicates that the reduction degree of the system gradually deepened. The thiol (HSR) and carboxylic acid ( $R'COOH$ ) ligands used in the system were finely adjusted ( $R$ :  $-CH(CH_3)_2 \rightarrow -CH(CH_3)(CH_2CH_3)$ ;  $R'$ :  $-CF_3 \rightarrow -CF_2CF_3$ ) and a similar phenomenon emerged in an attempt to characterize the generality of the process and identify some intermediates by the MDFI method (Fig. S6†). The solution components of the above-mentioned reaction were monitored by ESI-MS.

### Determination of intermediates by the mass difference fingerprint of isomorphism (MDFI) method

Identifying meaningful unknown species with large masses ( $m/z > 2000$ ) based on the ESI-MS data is a great challenge. By unrestrictedly matching  $m/z$  values, a lot of irreducible results can be obtained within the range of the allowable error. Of course, common methods (isotope (H/D) labeling) of determining  $H^-$  in H-rich metal NCs can be used, but at an unquestionably high cost. Inspired by a study on the hydrolysis process of lanthanide ( $Ln^{3+}$ ) clusters, to accurately determine the amount of a component of the species corresponding to the peaks from the ESI-MS data, an MDFI method that utilizes a certain mass difference of similar ligands to determine the exact number of the corresponding components in different species is proposed.<sup>15</sup> This method is based on the fact that similar experimental phenomena can still be observed when the relevant ligands ( $R$ :  $-CH(CH_3)_2 \rightarrow -CH(CH_3)(CH_2CH_3)$  or  $R'$ :  $-CF_3 \rightarrow -CF_2CF_3$ ) are changed in the reaction system (Fig. S6†). This result has inspired an encouraging speculation that they may have the same/similar growth process from an  $Ag^+$  ion to the target NC and intermediates during their formation. This MDFI method plays an important role in the subsequent identification of key intermediates (Scheme 1). For example, as



Scheme 1 Determination of key intermediates by the mass difference fingerprint of isomorphism (MDFI) method.  $z$  is the charge.

shown in Scheme 1, a peak observed in the ESI-MS spectrum of the  $\{^i\text{PrSAg}\}_n + \text{CF}_3\text{COOAg}$  system includes  $n$   $^i\text{PrS}^-$  and  $m$   $\text{CF}_3\text{COO}^-$  ligands, and the analogue including  $n$   $\text{CH}(\text{CH}_3)(\text{CH}_2\text{CH}_3)\text{S}^-$  or  $m$   $\text{C}_2\text{F}_5\text{COO}^-$  may be observed in the ESI-MS spectrum for  $\{\text{CH}(\text{CH}_3)(\text{CH}_2\text{CH}_3)\text{SAg}\}_n + \text{CF}_3\text{COOAg}$  or  $\{^i\text{PrSAg}\}_n + \text{C}_2\text{F}_5\text{COOAg}$  systems (Fig. 3 and S7, S8†), where only one variable was changed (Scheme 1). Thus, based on the mass difference ( $\Delta_1$  and  $\Delta_2$ ) and charges ( $z$ ), the number ( $n$  and  $m$ ) of related ligands ( $^i\text{PrS}^-$  and  $\text{CF}_3\text{COO}^-$ ) can be easily determined by using the related equation in Scheme 1. Note that this MDFI method is only used to rule out irreducible results. However, due to the presence of different ligands, it is normal that the peaks of related clusters do not conform to this phenomenon. For example, no peaks corresponding to the final product ( $[\text{Ag}_{70}\text{S}_4(\text{SCH}(\text{CH}_3)(\text{CH}_2\text{CH}_3))_{24}(\text{CF}_3\text{COO})_{20}]^{2-}$ ) were found (Fig. S6a†).

### Species assignment in solution

The time-dependent UV-vis spectra (Fig. 1) showed that the characteristic peak (*ca.* 530 nm) of  $\text{Ag}_{70}$  appeared after 4 h (Fig. S1†), corresponding to the color change of the mother liquor from yellow to orange. Interestingly, when the mother liquor changed to yellow (reaction time: 2–3 h), only a sharp characteristic absorption peak (416 nm) did not belong to  $\text{Ag}_{70}$  (Fig. S1d†), suggesting that intermediate substances may have been formed during the formation of  $\text{Ag}_{70}$ .

Time-dependent ESI-MS (Fig. 2 and S7, S8†) is used to confirm the presence of possible intermediates. Due to the complexity of the spectra and the presence of a large number of peaks, we focused on those peaks that appeared and intensified as the reaction proceeded. According to the real-time ESI-MS spectra, small  $\text{Ag}_n^+$  clusters protected by organic ligands ( $^i\text{PrS}^-$  and  $\text{CF}_3\text{COO}^-$ ), such as  $[\text{NH}_2(\text{CH}_3)_2]_x[\text{Ag}_{12+y}(\text{S}^i\text{Pr})_6(\text{CF}_3\text{COO})_{7+x+y}]^-$  ( $x = 0-4$ ,  $y = 0-3$ ), existed in the reaction solution from the beginning to the end (Fig. S7–S9†). After 12 h, clear peaks corresponding to  $\text{Ag}_{70}$  (Fig. S7†) began to appear at  $m/z = 5800-6300$  assignable to  $[\text{NH}_2(\text{CH}_3)_2]_x[\text{Ag}_{70}\text{S}_4(\text{S}^i\text{Pr})_{24}(\text{CF}_3\text{COO})_{20+x}]^{2-}$  ( $x = 0-4$ ), which

was consistent with the UV-vis results. Furthermore, the partial remaining peaks differ by a fixed value, 220 (assigned to  $\text{CF}_3\text{COOAg}$ ) and 159 (assigned to  $[\text{NH}_2(\text{CH}_3)_2\text{CF}_3\text{COO}]$ ), which also fully indicates that these small molecules are easily enriched on the surface of clusters in the mother liquor. An obvious peak of  $m/z = 5322.82$  attracted our attention, and its intensity gradually increased with the reaction time (2–12 h, Fig. 2b). Then it gradually decreased with the increase of  $\text{Ag}_{70}$  until it disappeared. This species is likely to be the intermediate/transition state that we are looking for. By employing the MDFI method, the number of  $\text{SR}^-$  and  $\text{R}'\text{COO}^-$  in this peak could be easily determined, and finally assigned to  $[\text{NH}_2(\text{CH}_3)_2]_4[\text{Ag}_{25}\text{S}(\text{SR})_8(\text{R}'\text{COO})_{16}]^-$  (denoted as  $\{\text{Ag}_{25}\text{S}\}$ ,  $\text{R} = -\text{CH}(\text{CH}_3)_2$  or  $-\text{CH}(\text{CH}_3)(\text{CH}_2\text{CH}_3)$ ;  $\text{R}' = -\text{CF}_3$  or  $-\text{CF}_2\text{CF}_3$ ; Fig. S6†). From the composition of the  $\{\text{Ag}_{25}\text{S}\}$  cluster, it was found that it has four free valence electrons and one  $\text{S}^{2-}$ , which may be the product of the reduction of monovalent Ag–S aggregates.

In addition to this  $\{\text{Ag}_{25}\text{S}\}$  (4e) species, another group of species with 9 free electrons,  $\{[\text{NH}_2(\text{CH}_3)_2]_3[\text{Ag}_{21+x}(\text{S}^i\text{Pr})_5(\text{CF}_3\text{COO})_{11+x}]\}^-$  ( $x = 0-2$ , denoted as  $\{\text{Ag}_{21}\}$ ,  $\{\text{Ag}_{22}\}$ , and  $\{\text{Ag}_{23}\}$ ), was observed. As observed in the intensity curve based on the ESI-MS data in Fig. 2b,  $\{\text{Ag}_{25}\text{S}\}$  species was the dominant product. It appeared after three hours of reaction and continued to increase as the reaction proceeded until it began to decrease after 18 hours. The  $\{\text{Ag}_{23}\}$  species exhibited a similar trend in the concentration curve, which means that it may have been transformed from  $\{\text{Ag}_{25}\text{S}\}$  species, and the increase in the number of free electrons is also reasonable. The intensities of  $\{\text{Ag}_{21}\}$ ,  $\{\text{Ag}_{22}\}$ , and  $\{\text{Ag}_{70}\text{S}_4\}$  species have increased since their appearance, and especially the curves of  $\{\text{Ag}_{21}\}$  and  $\{\text{Ag}_{70}\text{S}_4\}$  have the same trend (Fig. 2b). A similar phenomenon (Fig. S8†) was also observed during the reaction of increasing  $\{\text{Ag}(\text{S}^i\text{Pr})\}_n$ . So, the evolution of  $\{\text{Ag}_{70}\text{S}_4\}$  may follow such a path:  $\{\text{Ag}_{12-15}\}$  (0e)  $\rightarrow$   $\{\text{Ag}_{25}\text{S}\}$  (4e)  $\rightarrow$   $\{\text{Ag}_{21-23}\}$  (9e)  $\rightarrow$   $\{\text{Ag}_{70}\text{S}_4\}$  (20e), and the related detailed discussion is in the following part. Unfortunately, there is not much information available in positive ion mode ESI-MS to deepen our understanding of this process.

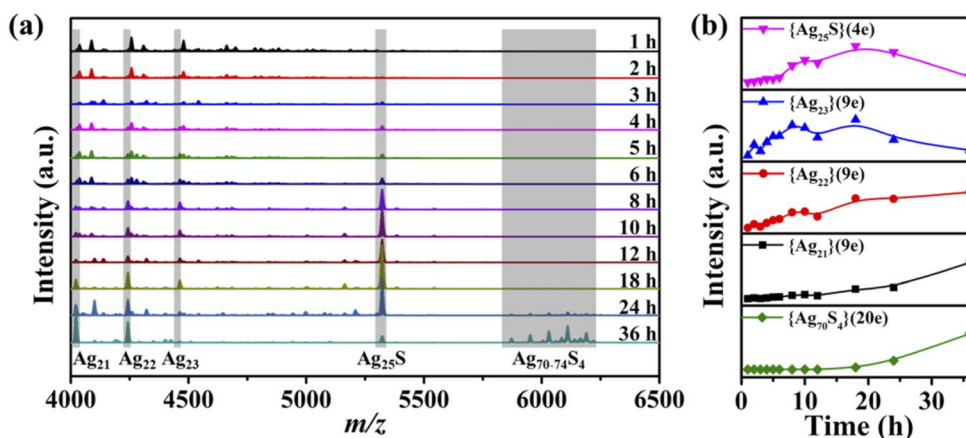


Fig. 2 Time-dependent ESI-MS spectra for the reaction solutions. (a) Negative ion mode ESI-MS data in the  $m/z$  range of 4000–6500 for the reaction solutions of 9 mg  $\{\text{Ag}(\text{S}^i\text{Pr})\}_n$ , 22 mg  $\text{CF}_3\text{COOAg}$ , and 50  $\mu\text{L}$   $\text{CF}_3\text{COOH}$  in the solvent mixture ( $^i\text{PrOH} : \text{DMF} = 3 : 1$ ) at  $80^\circ\text{C}$ . (b) Intensity-based curves of  $\{\text{Ag}_{25}\text{S}\}$ ,  $\{\text{Ag}_{23}\}$ ,  $\{\text{Ag}_{22}\}$ ,  $\{\text{Ag}_{21}\}$ , and  $\{\text{Ag}_{70}\text{S}_4\}$ .  $\{\text{Ag}_{70}\text{S}_4\} = [\text{Ag}_{70}\text{S}_4(\text{S}^i\text{Pr})_{24}(\text{CF}_3\text{COO})_{20}]^{2-}$ .





## Structural characterization

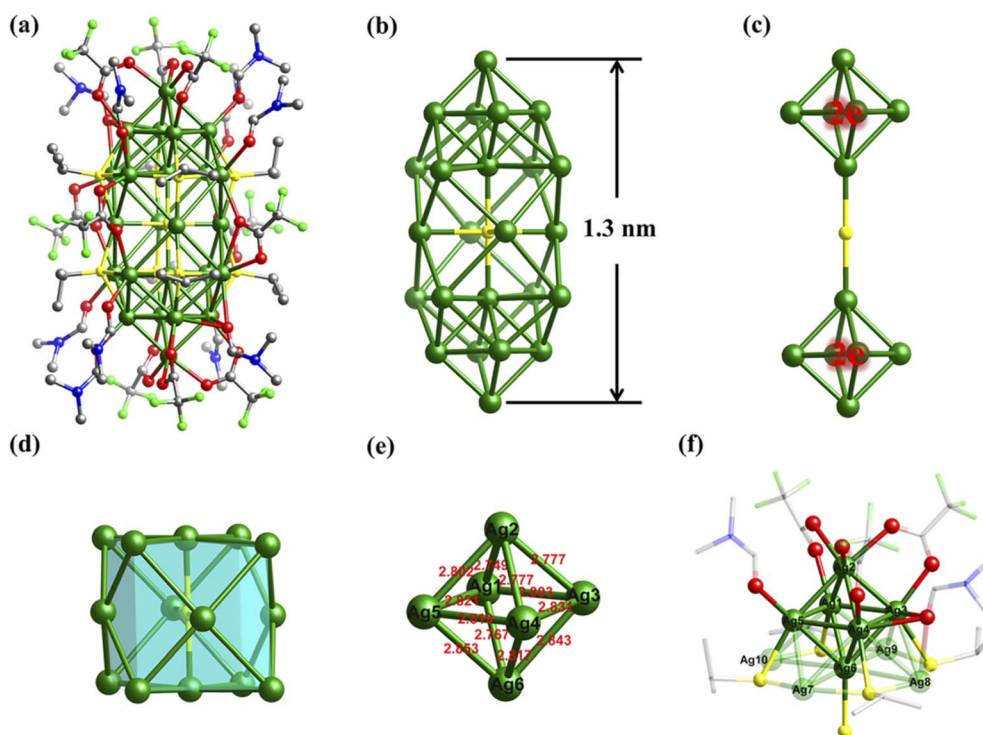
Based on ESI-MS analysis, considering the abundance increase of  $\{Ag_{25}S\}$  and other species in the early stage of the reaction, crystallization is quite helpful to determine their structures. Four kinds of crystals were obtained by evaporating the mother liquor at different reaction times at room temperature (Fig. S10†): colorless block ( $Ag_{14}$ , 0 h), yellow block ( $Ag_{24}$ , 3–6 h), black octahedral ( $Ag_{70} \cdot Ag_{12}$ , 8–24 h), and black rectangular ( $Ag_{70}$ , 36 h) crystals. If  $CF_3COOAg$  and  $CF_3COOH$  in the reaction are replaced by  $C_2F_5COOAg$  and  $C_2F_5COOH$ , respectively, two types of crystals were obtained: yellow block ( $Ag_{24} \cdot C_2F_5$ , 3 h), and black rectangular ( $Ag_{70} \cdot C_2F_5$ , 24 h) crystals.

The structures of the two black crystals ( $Ag_{70} \cdot Ag_{12}$  and  $Ag_{70}$ ) have been analyzed in a previous work, and  $Ag_{70} \cdot C_2F_5$  has the same structure (except for the different  $R'COO^-$  ligands) and similar cell parameters as  $Ag_{70}$ ; for more details please see ref. 14. The molecular structures of colorless ( $Ag_{14}$ , formula  $Ag_{14}(S^iPr)_6(CF_3COO)_8(DMF)_6$ ) and yellow block crystals ( $Ag_{24}/Ag_{24} \cdot C_2F_5$ , formula  $Ag_{24}S(S^iPr)_8(R'COO)_{10}(DMF)_8 \cdot 2(NH_2(CH_3)_2 \cdot R'COO)$ ,  $R' = -CF_3$  or  $-C_2F_5$ ) were determined by single-crystal X-ray diffraction (SCXRD) analysis (Tables S1–S3†) and elemental analysis. The structure of the  $\{Ag_{25}S\}$  species observed in ESI-MS should be  $Ag_{24}$  without DMF molecules, whose exposed parts are covered by additional  $CF_3COO^-$  and  $CF_3COOAg$ .

$Ag_{14}$  features an ellipsoidal  $Ag(I)$  cluster (Fig. S11†). Except that the middle silver ring expands from six to eight Ag atoms,

the silver–sulfur framework of  $Ag_{14}$  is similar to that of  $Ag_{12}$  in  $Ag_{70} \cdot Ag_{12}$  (Fig. S11†).<sup>14</sup>

Considering the structural similarity between  $Ag_{24}$  and  $Ag_{24} \cdot C_2F_5$  (Fig. S12†),  $Ag_{24}$  was selected as the representative for illustration (Fig. 3).  $Ag_{24}$  crystallizes in a triclinic space group ( $P\bar{1}$ ) and possesses half a cluster in the asymmetric unit (Fig. S12†). As is shown in Fig. 3a, the total structure of  $Ag_{24}$  presents a long strip shape, composed of one sulfur atom, 24 silver atoms, and organic ligands (eight  $S^iPr^-$ , ten  $CF_3COO^-$  and ten DMF molecules). The size of the “shuttle”-like  $S@Ag_{24}$  framework (Fig. 3b) is  $4.6 \times 4.6 \times 12.9 \text{ \AA}^3$ . The  $\mu_4-S^{2-}$  located in the inversion center (Fig. S13†) originates from the breaking of the  $S-C$  bond of  $S^iPr^-$ , and serves as an anion template here. The  $S^{2-}$ -template gathers 14 silver atoms together to form a slightly twisted cube ( $\mu_4-S@Ag_{14}$ , Fig. 3d and S14a†), where Ag atoms occupy the vertices and the center of the faces ( $Ag-S$  bond lengths: 2.537(2) and 2.621(4)  $\text{\AA}$ ; the distances of  $Ag \cdots Ag$ : 3.212(4) to 3.464(4)  $\text{\AA}$ , Table S3†). Interestingly, two classical  $Ag_6$  octahedra appear on both sides of the above polyhedron (Fig. 3c and S14b†). The three parts merge into the final skeleton ( $Ag(S@Ag_{14}) \cdots Ag(Ag_6)$ : 3.057(3) to 3.171(3)  $\text{\AA}$ ) by sharing silver atoms (Fig. 3b). The 8  $S^iPr^-$  ligands with a  $\mu_4$  mode, located at the junction of the  $S@Ag_{14}$  fragment and the  $Ag_6$  motifs, hold them firmly together (Fig. S13†). The  $Ag-S(S^iPr^-)$  bond lengths are located in the range of 2.395(6) to 2.576(9)  $\text{\AA}$  (Table S3†). Due to differences in location, the 10  $CF_3COO^-$  ligands are divided into two types (Fig. 3a and S15†): (i) the four with  $\mu_2-\eta^1:\eta^1$  or  $\mu_3-\eta^1:\eta^2$  modes cap at the waist; (ii) the six with  $\mu_2-\eta^1:\eta^1$  mode



**Fig. 3** The crystal structure of  $Ag_{24}$ . (a) Ball-and-stick representation of the overall structure. (b) The ‘shuttle’-like 24-Ag-atom skeleton. (c) Two  $Ag_6^{4+}$  octahedra separated by  $S^{2-}$ . (d) The cubic body  $S@Ag_{14}$  in the middle of  $Ag_{24}$ . (e) Structural details and (f) coordination environments of  $Ag_6^{4+}$ . Atom color codes: green, Ag; yellow, S; red, O; bright green, F; blue, N; grey, C. All hydrogen atoms are omitted for clarity.



cover the  $\text{Ag}_6$ . The  $\text{Ag}-\text{O}(\text{CF}_3\text{COO}^-)$  bond lengths span from 2.26(4) to 2.72(2) Å. Ten additional DMF molecules finally finish the outer organic shell ( $\text{Ag}-\text{O}(\text{DMF})$  bond: 2.27(3) to 2.87(6) Å) to protect and stabilize the  $\text{S@Ag}_{24}$  kernel (Fig. S16†).

It is worth noting that the  $\text{Ag}\cdots\text{Ag}$  distances of  $\text{Ag}_6$  species range from 2.767(4) to 2.853(3) Å with an average of 2.805 Å (Fig. 3e), which is shorter than others (3.057(3) to 3.464(4) Å) of  $\text{Ag}_{24}$  and those of metallic Ag (2.88 Å), indicating the presence of significantly stronger argentophilic interactions. The  $\text{Ag}\cdots\text{Ag}$  distances of the  $\text{Ag}_6$  fragments in  $\text{Ag}_{24}$  are comparable to those of reported  $\text{Ag}_6^{4+}$  cores with similar configurations (2.66–2.87 Å),<sup>10b,16</sup> but shorter than those of  $\text{Ag}_6^{6+}$  octahedra (2.85–3.44 Å, Table S4†).<sup>10c,17</sup> Therefore, the  $\text{Ag}_6$  kernels in  $\text{Ag}_{24}$  should also be  $\text{Ag}_6^{4+}$  with two delocalized electrons. Moreover, unlike previously reported  $\text{Ag}_6^{4+}$  octahedra located in the center of the Ag clusters, two  $\text{Ag}_6^{4+}$  fragments in  $\text{Ag}_{24}$  are on the periphery and stabilized by weak Ag–O bonds (2.27(3) to 2.63(7) Å, Fig. 3f), suggesting that this cluster is highly reactive.

When the  $\text{Ag}_{24}$  crystals were dissolved in  $\text{CH}_2\text{Cl}_2$ , no obvious signal appeared in the ESI-MS spectra. An additional amount of DMF (Fig. S17†) or  $^i\text{PrOH}$  (Fig. S18†) was introduced, and the ESI-MS spectra showed a series of  $\text{Ag}_{24}$ -related peaks (1a–1i, Tables S5; and 2a–2n, S6†) in both positive and negative ion modes, including the high intensity peak assigned to  $[\text{NH}_2(\text{CH}_3)_2]_4[\text{Ag}_{25}\text{S}(\text{S}^i\text{Pr})_8(\text{CF}_3\text{COO})_{16}]^-$  (2d, calcd  $m/z = 5322.83$ ) in the mother liquor. These groups of peaks showed strong correlation, which indicated that different numbers of small ions and/or molecules ( $\text{Ag}^+$ ,  $\text{NH}_2(\text{CH}_3)_2^+$ , and  $\text{CF}_3\text{COO}^-$ ) were attached to the main structure  $[\text{Ag}_{24}\text{S}(\text{S}^i\text{Pr})_8(\text{CF}_3\text{COO})_{10}]$  (Fig. S17f and S18d†). So,  $\text{Ag}_{24}$  is a rare 4e cluster ( $n = 24 - 2 - 8 - 10$ ) with two independent 2e delocalized  $\text{Ag}_6^{4+}$  based on the above SCXRD and ESI-MS analysis.

The UV-vis spectrum of  $\text{Ag}_{24}$  showed three prominent optical absorption bands at 345, 377 and 422 nm (Fig. 4a). To reveal the electronic structure of  $\text{Ag}_{24}$ , we carried out density functional theory (DFT) and time-dependent density functional theory (TD-DFT) calculations. The calculated spectrum correlated well with the experimental one, and the details of the transitions ( $\alpha$ ,  $\beta$ ,  $\gamma$ ; Fig. 4b and S19–S26†) are summarized in Table S7.† The  $\alpha$ ,  $\beta$ , and  $\gamma$  peaks correspond to  $\text{HOMO}-2/\text{HOMO}-1/\text{HOMO} \rightarrow \text{LUMO}$ ,  $\text{HOMO}-3/\text{HOMO}-2/\text{HOMO}-1/\text{HOMO} \rightarrow \text{LUMO}+1/\text{LUMO}+2/\text{LUMO}+3$ , and  $\text{HOMO}-15/\text{HOMO}-10/\text{HOMO}-8/\text{HOMO}-5/\text{HOMO}-3 \rightarrow \text{LUMO}/\text{LUMO}+2/\text{LUMO}+4$  transitions, respectively. The HOMO is composed of two spherical harmonics with S character, originating at the two  $\text{Ag}_6^{4+}$  centers, while the LUMO,  $\text{LUMO}+1/2$ , and  $\text{LUMO}+3/4$  states show 1P symmetry at  $\text{Ag}_6^{4+}$  (Fig. 4c).<sup>10b,16g</sup>

### The determination of the key intermediate

Whether  $\text{Ag}_{24}$  is an intermediate in the formation of  $\text{Ag}_{70}$  is the most important issue to reveal the structural evolution and size expansion during the reduction process. To solve this confusion, we tried to obtain the final product ( $\text{Ag}_{70}$ ) with  $\text{Ag}_{24}$  crystals as the raw material. When the yellow crystals of  $\text{Ag}_{24}$  were dissolved in MeOH (Video S1†), EtOH or  $^i\text{PrOH}$ , the color of the solution turned red or brown within 5 s. This means that upon stimulation by solvent molecules, the surface ligands of the highly active  $\text{Ag}_{24}$  were removed, and the more active species clustered to assemble into larger aggregates instead of disintegrating. The ESI-MS spectra of the obtained solution (Fig. 5a and S27†) confirmed the formation of larger species including  $\text{Ag}_{70}$ , which directly confirmed that  $\text{Ag}_{24}$  was a necessary intermediate in the formation of  $\text{Ag}_{70}$ , rather than a simple unrelated kinetic product. The medium-sized  $\{\text{Ag}_{49-52}\}$  species observed in the transition process arise as a result of the fragmentation of  $\text{Ag}_{70}$ .<sup>14</sup> Additional  $\text{CF}_3\text{COOAg}$  molecules can inhibit the formation of these fragments (Fig. 5a).

Time-dependent absorption spectra (Fig. 5b) are used to track and monitor the transformation process from  $\text{Ag}_{24}$  (prominent peaks in  $\text{CH}_2\text{Cl}_2$ : 345, 377 and 422 nm) to  $\text{Ag}_{70}$  (distinct absorption bands: 335, 386, 426, 530, and 595 nm in DMF). From 0 h to 6 h, the absorption peaks of 400–450 nm and

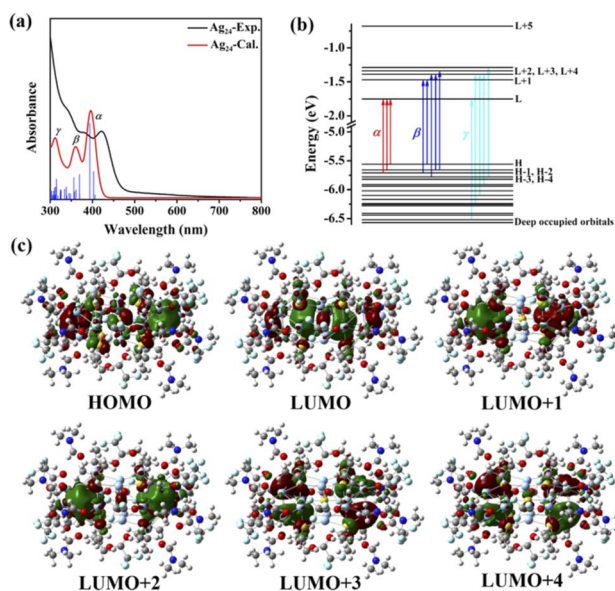


Fig. 4 UV-vis absorption spectra and DFT of  $\text{Ag}_{24}$ . (a) Experimental (black) and calculated (red) absorption spectra of  $\text{Ag}_{24}$  in  $\text{CH}_2\text{Cl}_2$ . (b) The Kohn–Sham orbital energy level of  $\text{Ag}_{24}$ . (c) Frontier orbitals including HOMO, LUMO, LUMO+1, LUMO+2, LUMO+3 and LUMO+4 of  $\text{Ag}_{24}$ .

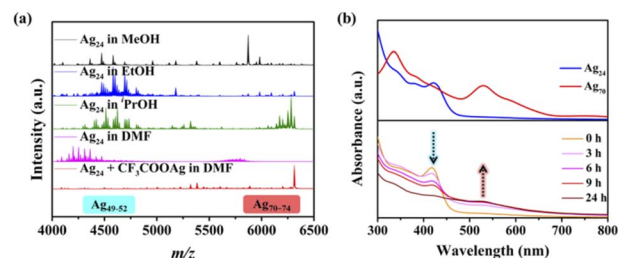


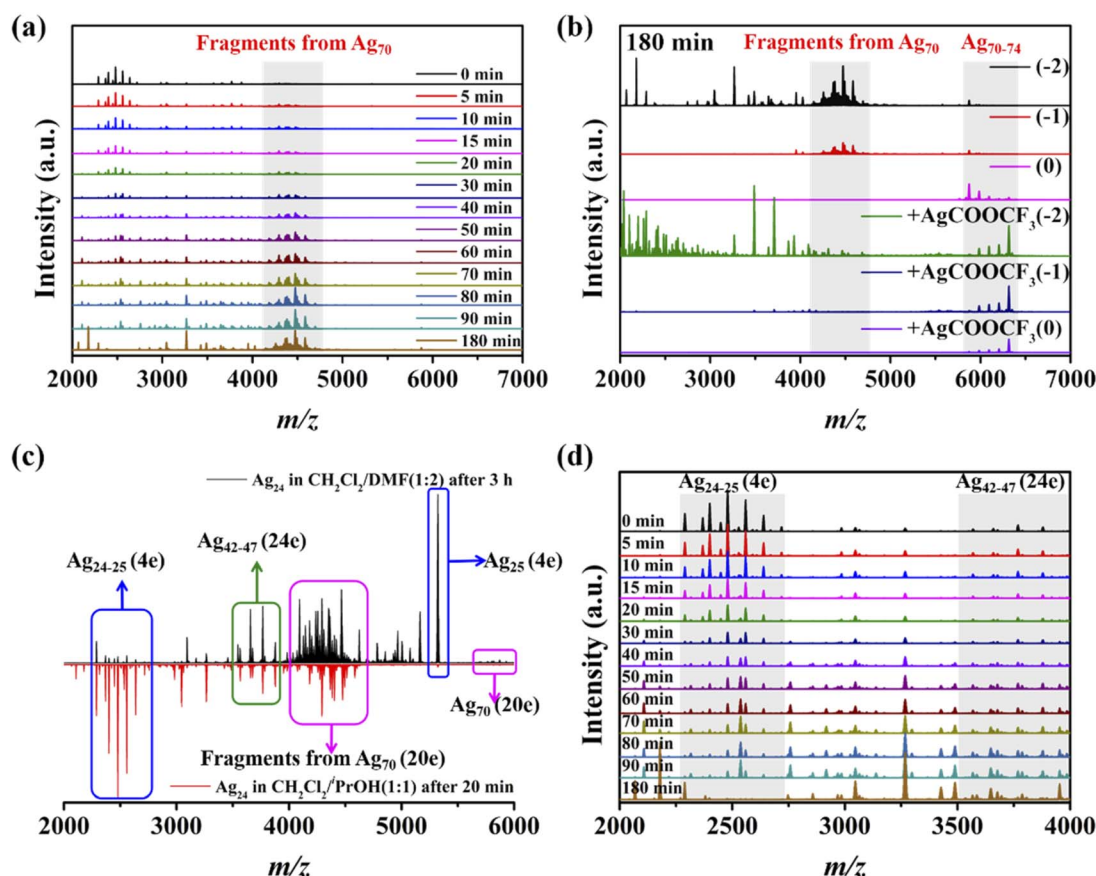
Fig. 5 Tracking the transformation process from  $\text{Ag}_{24}$  to  $\text{Ag}_{70}$  by ESI-MS and UV-vis spectroscopy. (a) Negative-ion mode ESI-MS spectra of  $\text{Ag}_{24}$  in different solutions. (b) Top: UV-vis absorption spectra of  $\text{Ag}_{24}$  (dissolved in  $\text{CH}_2\text{Cl}_2$ ) and  $\text{Ag}_{70}$  (dissolved in DMF); Bottom: time-dependent UV-vis absorption spectra of  $\text{Ag}_{24}$  (yellow solution) to  $\text{Ag}_{70}$  (red solution).

below 400 nm were attenuated, and the absorption between 450 and 800 nm was enhanced gradually. After 6 h, the spectrum showed three distinct peaks at 340, 423 and 530 nm, and the solution color was changed from yellow to red. Furthermore, ESI-MS was used to analyze the products of the structural conversion (Fig. S28†), and the results were similar to the ESI-MS spectra of  $\text{Ag}_{24}$  dissolved in MeOH. This transition process ( $\text{Ag}_{24} \rightarrow \text{Ag}_{70}$ ) was slowed down in DMF, possibly due to the presence of a large number of DMF molecules on the cluster surface, which passivated the active  $\text{Ag}_6^{4+}$  core.

### Evolution route from $\text{Ag}_{24}$ to $\text{Ag}_{70}$

The growth process of small  $\text{Ag}_{24}$  to  $\text{Ag}_{70}$  by self-reaction is crucial for understanding and controlling the preparation of large-sized Ag nanoclusters. Initial attempts using ESI-MS to identify reaction intermediates in an alcohol solution were unsuccessful because the transition reaction was completed quickly (<1 min). To suppress the reaction kinetics of the system, we tried to trigger reactions of  $\text{Ag}_{24}$  to  $\text{Ag}_{70}$  with mixed solvents (such as  $\text{CH}_2\text{Cl}_2$  and MeOH, Video S2†). After much trial and error, suitable real-time ESI-MS spectra were obtained for the systems of  $\text{CH}_2\text{Cl}_2 + {}^1\text{PrOH}$  (1 : 1, Fig. 6) and  $\text{CH}_2\text{Cl}_2 +$

DMF (1 : 2, Fig. S29†). As shown in Fig. 6, with the reaction going on, it was clear that the peak intensity of  $\{\text{Ag}_{24-25}\text{S}\}$  (4e) with two negative charges in the  $m/z = 2250\text{--}2750$  decreases continuously, while the peaks of  $\text{Ag}_{70}$  began to appear slowly and strengthen. By adjusting the collision voltages and adding  $\text{CF}_3\text{COOAg}$ , it was proved that the group peaks in the  $m/z = 4100\text{--}4900$  were the result of the fragmentation of the  $\text{Ag}_{70}$  cluster (Fig. 6a and b). The two systems have similar peak groups and changing trends in negative ion mode ESI-MS (Fig. 6c and S29†). In the positive ion mode ESI-MS, no new peaks appeared in the  $\text{CH}_2\text{Cl}_2/{}^1\text{PrOH}$  system, while in  $\text{CH}_2\text{Cl}_2/\text{DMF}$ , there were new peaks in the  $m/z = 4200\text{--}4800$  denoted as  $\{[\text{NH}_2(\text{CH}_3)_2]_{10+x}\text{Ag}_{18+y}\text{S}(\text{S}^i\text{Pr})_5(\text{CF}_3\text{COO})_{12+x+y}(\text{DMF})\}^+$  ( $x = 0\text{--}3$ ,  $y = 0\text{--}1$ , Fig. S29b–d and Table S8†), containing 8 free valence electrons. The peaks (4a–4i) with two negative charges in the  $m/z = 3500\text{--}4000$  were assigned to  $\{[\text{NH}_2(\text{CH}_3)_2]_8[\text{Ag}_{42+x}\text{S}_4(\text{S}^i\text{Pr})_{11}(\text{CF}_3\text{COO})_{9+x}]\}^{2-}$  ( $x = 0\text{--}5$ , Fig. S30 and Table S9†) containing 24 free valence electrons. The highly reduced  $\{\text{Ag}_{42-47}\text{S}_4\}$  (24e) species with four  $\text{S}^{2-}$  anions may have formed an initial  $\text{Ag}_n\text{S}_4$  core similar to the  $\text{Ag}_{70}$  (20e) cluster. Compared to  $\text{Ag}_{70}$  ( $[\text{Ag}_{70}\text{S}_4(\text{S}^i\text{Pr})_{24}(\text{CF}_3\text{COO})_{20}]^{2-}$ ), the inconsistent electron numbers, and missing metal atoms and ligands of



**Fig. 6** Time-dependent ESI-MS spectra from  $\text{Ag}_{24}$  to  $\text{Ag}_{70}$  dissolved in the solvent mixture ( ${}^1\text{PrOH} : \text{CH}_2\text{Cl}_2 = 1 : 1$ ). (a) Time-dependent negative ion mode ESI-MS (collision energy: 2 V) in the range of  $m/z = 2000\text{--}7000$  of  $\text{Ag}_{24}$  for tracking the transformation process from  $\text{Ag}_{24}$  to  $\text{Ag}_{70}$ . (b) ESI-MS data at different collision voltages (0, 1, 2 V) after  $\text{Ag}_{24}$  was dissolved in the solvent mixture ( ${}^1\text{PrOH} : \text{CH}_2\text{Cl}_2 = 1 : 1$ ) for three hours, and ESI-MS data after adding  $\text{CF}_3\text{COOAg}$  salt as a comparison. (c) Comparison of the transformation process from  $\text{Ag}_{24}$  to  $\text{Ag}_{70}$  in different solvents. (d) Time-dependent negative ion mode ESI-MS (collision energy: 2 V) in the range of  $m/z = 2000\text{--}4000$ , highlighting some key intermediates.



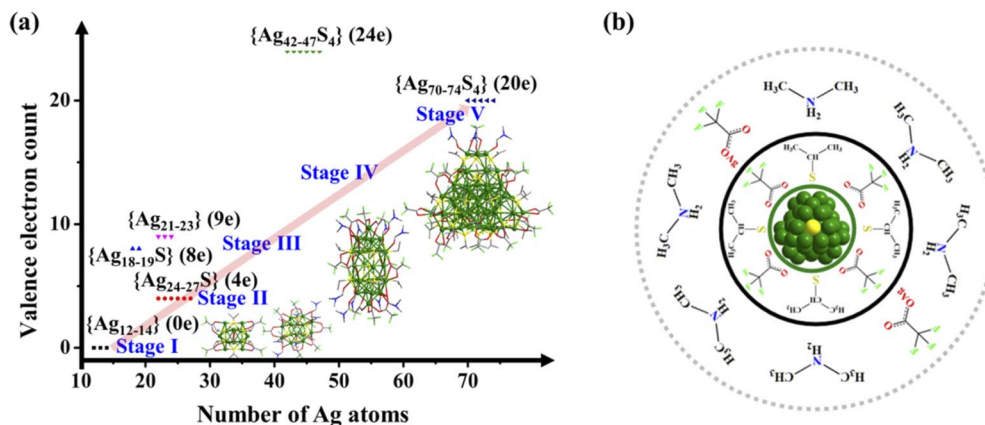


Fig. 7 Schematic illustration of the growth process of  $\text{Ag}_{70}$  and the general structure of related species. (a) Schematic illustration of the growth process. Five stages dominated by different reaction processes are shown. Stage I: aggregate; stage II: reduction; stage III: decomposition and recombination; stage IV: fusion and stage V: surface recombination and motif enrichment. (b) General structure of relevant clusters during the synthesis of  $\text{Ag}_{70}$ : Ag–S cores of relevant clusters are protected by organic ligands;  $[\text{NH}_2(\text{CH}_3)_2]^+$  ions and  $\text{CF}_3\text{COOAg}$  molecules are attached to the periphery.

$\{\text{Ag}_{42-47}\text{S}_4\}$  (24e) suggest that they may still need to undergo oxidation or local decomposition, and further Ag–S shell reconstruction to form the final products. It is worth noting that there are still some peaks that are not assigned properly due to the complexity of the system.

Based on the above observations and analysis, a reasonable stepwise bottom-up evolution route of  $\text{Ag}_{70}$  (Fig. 7a) is provided, including five stages: stage I, small molecules ( $\text{CF}_3\text{COOAg}$  and  $\text{AgS}^{\text{iPr}}$ ) aggregate to form stable monovalent clusters, such as  $\{\text{Ag}_{12-14}\}$ ; stage II, at a certain acidity, DMF serving as both a mild reducing reagent and an organic reaction medium effectively reduces small Ag fragments (such as  $[\text{NH}_2(\text{CH}_3)_2]_x[\text{Ag}_{12+y}(\text{S}^{\text{iPr}})_6(\text{CF}_3\text{COO})_{7+x+y}]^-$  ( $x = 0-4$ ,  $y = 0-3$ ,  $\{\text{Ag}_{12-15}\}$  (0e)), Fig. S7–S9†) to classical face-centered cubic (fcc)  $\text{Ag}_6^{4+}$  species. The  $\text{Ag}_6^{4+}$  reducing fragments are passivated by  $\text{S}^{2-}$  templates *in situ* generated from the breaking of the S–C bond of organic ligands, forming relatively stable  $\{\text{Ag}_{24-27}\text{S}\}$  (4e) clusters containing a  $\text{S}@\text{(Ag}_6)_2$  skeleton (Fig. 2 and S17, S18†); stage III,  $\text{Ag}_{24}$  disintegrate and recombine to form intermediates with more free electrons, such as  $\{[\text{NH}_2(\text{CH}_3)_2]_3[\text{Ag}_{21+x}(\text{S}^{\text{iPr}})_5(\text{CF}_3\text{COO})_{11+x}]^-\}$  ( $x = 0-2$ ,  $\{\text{Ag}_{21-23}\}$  (9e), Fig. 2 and S7–S9†) and  $\{[\text{NH}_2(\text{CH}_3)_2]_{10+x}\text{Ag}_{18+y}\text{S}(\text{S}^{\text{iPr}})_5(\text{CF}_3\text{COO})_{12+x+y}(\text{DMF})\}^+$  ( $x = 0-3$ ,  $y = 0-1$ ,  $\{\text{Ag}_{18-19}\text{S}\}$  (8e), Fig. S29†); stage IV, the small reducing products described above assemble and fuse together to form 4  $\text{S}^{2-}$ -passivated preliminary products,  $\{[\text{NH}_2(\text{CH}_3)_2]_8[\text{Ag}_{42+x}\text{S}_4(\text{S}^{\text{iPr}})_{11}(\text{CF}_3\text{COO})_{9+x}]^{2-}\}$  ( $x = 0-5$ ,  $\{\text{Ag}_{42-47}\text{S}_4\}$  (24e), Fig. S30 and Table S9†); stage V, on the basis of  $\{\text{Ag}_{42-47}\text{S}_4\}$  (24e), oxidation or localized decomposition occurs and extra small molecules accumulate on the surface to form the final product  $\text{Ag}_{70}$  (Fig. S31†) with a multi- $\text{S}^{2-}$ -passivated  $\text{Ag}_{28}^{8+}$  kernel (20e) possessing an fcc  $\text{Ag}_{16}$  inner core. It can be seen that the formation process of  $\text{Ag}_{70}$  nanoclusters is different from that of typical Ag NCs (lowly reduced species with a similar number of metal as the product is formed first, and is further reduced) and Au NCs (step-by-step formation process).<sup>11</sup>

Interestingly, these observed intermediate species and products have similar structural features (Fig. 7b): the silver or silver–sulfur framework protected by organic ligands ( $\text{CF}_3\text{COO}^-$  and  $\text{S}^{\text{iPr}-}$ ) is always enriched with some  $[\text{NH}_2(\text{CH}_3)_2]^+$  ions and  $\text{CF}_3\text{COOAg}$  molecules based on electrostatic and hydrogen bonding interactions at the periphery. The introduction of additional  $[\text{NH}_2(\text{CH}_3)_2]^+$  cations can significantly improve yields, as do other similar amine cations. These species are critical for stabilizing intermediates and forming products. Uncovering the formation process of this medium-scale nanocluster is of great importance since it maps out a reasonable and common avenue for the generation and expansion of the fcc metal kernel in metal nanoclusters.

## Conclusions

In summary, the reaction process of  $\text{Ag}_{70}$  was traced by time-dependent UV-vis spectroscopy and ESI-MS. The intermediates ( $\text{Ag}_{14}$  and  $\text{Ag}_{24}$ ) were crystallized successfully by controlling the reaction time. A reasonable path from  $\text{Ag}^+$  species (such as  $\text{Ag}_{14}$ ) to  $\text{Ag}_{24}$  (skeleton:  $\text{S}@\text{(Ag}_6^{4+})_2$ ), and then to  $\text{Ag}_{70}$  (multi- $\text{S}^{2-}$ -induced kernel:  $\text{Ag}_{28}^{8+}$ ) has been mapped out. The detailed process of bottom-up assembly from  $\text{Ag}_{24}$  to  $\text{Ag}_{70}$  was successfully revealed by real-time ESI-MS. The evolutionary route suggests that small cations for stabilization and highly reactive reducing species are critical for the formation of large-sized Ag NCs. Overall, this work presents a reasonable avenue for comprehending the generation and expansion of an fcc core in metal NCs, and provides some guidance for controlled synthesis of NCs and nanoparticles in the future.

## Data availability

All the data supporting this article have been included in the main text and the ESI.† The X-ray crystallographic coordinates for structures reported in this article have been deposited at the



Cambridge Crystallographic Data Centre (CCDC) under deposition numbers CCDC: 2182448, 2182449, and 2182450.

## Author contributions

S. Q. Z. conceived and designed the experiments. X. M. L. and S. H. conducted the synthesis and characterization. X. M. L. drew the pictures in the manuscript. S. Q. Z., X. Y. D. and X. M. L. analysed the experimental results. X. M. L. and K. M. completed crystallographic data collection and refinement of the structure. P. L. performed the calculations. Z. Y. W. helped to revise the writing. X. M. L., X. Y. D., and S. Q. Z. co-wrote the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 21825106, U21A20277, 92061201, and 21975065) and Zhengzhou University.

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