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Introduction

Ligand-protected nanoclusters have attracted significant attention due to their promising applications in catalysis, optical waveguides, fluorescence, and more.¹⁻⁹ The increasing number of structurally-determined clusters has led to the discovery of various types of nanocluster isomerism, including chiral isomerism and structural isomerism, which serve as valuable for investigating models structure-property relationships.¹⁰⁻¹⁷ Chiral isomerism is often observed in the crystal lattice, while structural isomerism can be achieved through ligand engineering or controlled synthesis methods. However, compared to chiral isomerism, the existence of "literal" nanocluster structural isomers, composed of identical constituent metals and ligands, is rarely reported. To date,

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An insight, at the atomic level, into the structure and catalytic properties of the isomers of the Cu_{22} cluster \dagger

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The study of structural isomerism in copper nanoclusters has been relatively limited compared to that in gold and silver nanoclusters. In this work, we present the controlled synthesis and structures of two isomeric copper nanoclusters, denoted as Cu_{22} -1 and Cu_{22} -2, whose compositions were determined to be $Cu_{22}(\text{SePh})_{10}(\text{Se})_6(\text{P(Ph-}^4\text{F})_3)_8$ through single-crystal X-ray diffraction (SCXRD). The structural isomerism of Cu_{22} -1 and Cu_{22} -2 arises from the different arrangements of a few $Cu(\text{SeR})(\text{PR}_3)$ motifs on the surface structure. These subtle changes in the surface structure also influence the distortion of the core and the spatial arrangement of the clusters, and affect the electronic structure. Furthermore, due to their distinct structures, Cu_{22} -1 and Cu_{22} -2 exhibit different catalytic properties in the copper-catalyzed [3 + 2] azide–alkyne cyclo-addition (CuAAC). Notably, Cu_{22} -1 demonstrates efficient catalytic activity for photoinduced AAC, achieving a yield of 90% within 1 hour. This research contributes to the understanding of structural isomerism in copper nanoclusters and offers insights into the structure–function relationship in these systems.

only seven pairs of such isomers have been fully structurally determined, namely Au₄Cu₄,¹⁸ Au₉,¹⁹ Au₂₃,¹⁰ Au₂₈,²⁰ Au₃₆,²¹ Au_{38} ,²² and Au_{42} .²³ The discovery of structural isomerism has greatly contributed to our understanding of the correlation between cluster structures and their properties. For instance, the $Au_{36}(SR)_{24}$ cluster, with a two-dimensional (2D) arrangement of Au4 tetrahedral units, has been found to exhibit higher efficiency in the intramolecular hydroamination of alkynes compared to the Au₃₆(SR)₂₄ cluster with a one-dimensional (1D) arrangement of Au₄ tetrahedral units.²⁴ Similarly, two isomeric $Au_{38}(PET)_{24}$ (PET = 2-phenylethanethiol) clusters have demonstrated distinctly different catalytic properties, while two isomeric $Au_{42}(TBBT)_{26}$ (TBBT = 4-tert-butylbenzenethiol) clusters have exhibited diverse luminescence behaviors.^{22,23} Efforts have been made to discover more pairs of nanocluster structural isomers.^{25–39} The majority of research on structural isomerism in nanoclusters has focused on gold and silver nanoclusters, with limited exploration of copper nanocluster structural isomerism.^{31,40,41} Quasi-structural isomerism has been identified in copper clusters based on the $Cu_{20}H_{11}(S_2P(O^iPr)_2)_9$ and $Cu_{20}H_{11}\{Se_2P(O^iPr)_2\}_9$ templates.⁴⁰ Then the Sun group synthesized two quasi-structurally isocopper nanoclusters, $[Cu_{13}Na_2(CZ-PrA)_6(TC_4A)_2Cl$ meric $(CH_3OH)_2$ and $[Cu_{13}Na(CZ-PrA)_6(TC_4A)_2(CH_3OH)] \cdot CH_3OH \cdot$ CH₂Cl₂·CH₃COCH₃, with nearly identical Cu₁₃ cores but different ligand arrangements. This difference results in varied catalytic selectivity for the ¹O₂ involved selective oxidation of sulfides.41 Unlike the quasi-structural isomerism observed in



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 $[\]dagger$ Electronic supplementary information (ESI) available: Synthesis process, characterization, X-ray analysis, and Fig. S1, S12 and Tables S1–S6 offering more details on the nanoclusters Cu₂₂-1 and Cu₂₂-2. CCDC 2289673 for Cu₂₂-1 and 2289674 for Cu₂₂-2. For ESI and crystallographic data in CIF or other electronic format see DOI: https://doi.org/10.1039/d4nr00973h

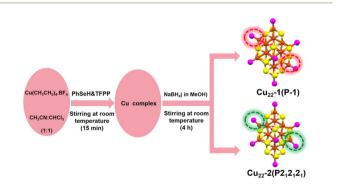
copper nanoclusters, reports of copper cluster isomers sharing the same molecular formula yet exhibiting different structures are exceedingly rare. Therefore, further investigations are necessary to explore the isomerism of copper nanoclusters.

In this study, we present the synthesis of two isomeric copper nanoclusters, namely Cu₂₂-1 and Cu₂₂-2, through the reduction of a copper salt (Cu(CH₃CN)₄·BF₄) in the presence of PhSeH and P(Ph- ${}^{4}F$)₃ ligands. The compositions of Cu₂₂-1 and Cu_{22} -2 were determined to be $Cu_{22}(SePh)_{10}(Se)_6(P(Ph-{}^4F)_3)_8$. The Se^{2-} in the clusters may be generated *in situ* by the decomposition of the PhSe⁻ ligands, whose C-Se bonds are broken under the reducing atmosphere.^{42,43} Interestingly, during the crystal culture process, Cu22-1 and Cu22-2 formed crystals with different crystal forms (Fig. S1[†]), enabling easy separation and subsequent analysis using single-crystal X-ray diffraction. Although Cu22-1 and Cu₂₂-2 exhibit slight structural differences, they display distinct packing modes and demonstrate unique catalytic properties. This discovery of copper isomerism protected by PhSe⁻ and P(Ph-⁴F)₃ ligands contributes to the advancement of structural isomerism in this field.

Results and discussion

The synthesis of the two isomeric $Cu_{22}(SePh)_{10}(Se)_6(P(Ph-{}^4F)_3)_8$ clusters was achieved using a one-pot method, followed by a crystal culture process to separate them (Scheme 1). In this procedure, Cu(CH₃CN)₄·BF₄ was added to a mixed solution of CH₃CN and CHCl₃. After 10 minutes, tris(4-fluorophenyl)phosphine $(P(Ph-{}^{4}F)_{3})$ and phenylselenol (PhSeH) were introduced. After an additional 15 minutes, a NaBH₄ solution was added. The resulting mixture was stirred for 4 hours, and then the solution was removed using a rotary evaporator. The obtained precipitate was washed multiple times with CH₂Cl₂ and *n*-hexane. The $Cu_{22}(SePh)_{10}(Se)_6(P(Ph-{}^4F)_3)_8$ isomers were crystallized in a mixture of CH₂Cl₂ and *n*-hexane at room temperature for 2 weeks. Black block and yellow flake crystals were observed, which were identified as Cu22-1 and Cu22-2, respectively. The yield of the nanoclusters was about 10% and 15% for black block Cu₂₂-1 and yellow flake Cu₂₂-2, respectively.

Single-crystal structural analysis revealed both copper nanoclusters have identical compositions. Each consisted of 22



Scheme 1 The synthesis method of Cu₂₂-1 and Cu₂₂-2.

copper atoms, 10 PhSe⁻ ligands, 8 P(Ph-⁴F)₃ and 6 Se atoms, but they had different surface structures. The total structures of Cu₂₂-1 and Cu₂₂-2 are shown in Fig. 1. The overall structures of Cu₂₂-1 and Cu₂₂-2 are very similar, and the structural isomerism of Cu₂₂-1 and Cu₂₂-2 mainly resulted from different arrangements of a few Cu(SeR)(PR₃) motifs which was highlighted by the red and green circles. It is worth noting that the structure of Cu₂₂-1 was similar to the structures of $[Cu_{22}Se_6(SePh)_{10}(PPh_2C_6H_4SMe)_8]^{44}$ and $[Cu_{22}Se_6(S-C_6H_4 Br)_{10}(PPh_3)_8]/[Cu_{22}Se_6(S-C_6H_4-OSiMe_3)_{10}(PPh_3)_8]$ reported by the Fuhr group,^{45,46} while Cu₂₂-2 had not been observed.

The structures of Cu22-1 and Cu22-2 were analysed and are presented in Fig. 2. Both clusters had similar Cu₁₆Se₆ units, which were formed by the fusion of two distorted Ino decahedra Cu₁₀Se₃ through the sharing of four Cu atoms (Fig. S2[†] and Fig. 2A and B). As shown in Fig. S3,† the arrangement of the $Cu_{16}Se_6$ units in Cu_{22} -2 was more orderly than that in Cu₂₂-1. The Cu₁₆Se₆ framework was then surrounded by two $Cu(SeR)_3(PR_3)$ motifs. The isomeric structures of Cu_{22} -1 and Cu_{22} -2 were achieved when the surface $Cu_2(SeR)_2(PR_3)_2$ motifs capped the Cu16Se6@Cu2(SeR)6(PR3)2 framework. As shown in Fig. 2C and D, the difference in the bonding environment of the $Cu_2(SeR)_2(PR_3)_2$ motifs with the $Cu_{16}Se_6(Cu_2(SeR)_6(PR_3)_2)$ framework can be observed, especially for the copper atoms (blue). The copper atoms in blue shift from the position near $Cu(SeR)_3(PR_3)$ to the position of the nucleus, accompanied by the bond distance of Cu_{blue}-Se_{red} varying from 2.587 Å to 4.604 Å, and the bond distance of Cublue-Seyellow varying from 4.446 Å to 2.553 Å (Fig. S4†). Therefore, the different arrangements of the surface motifs account for the isomerism of Cu22-

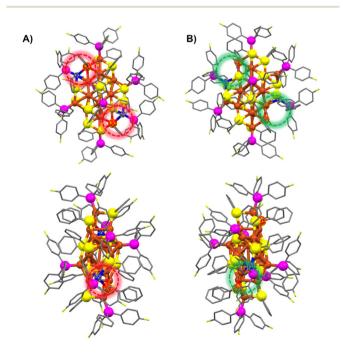
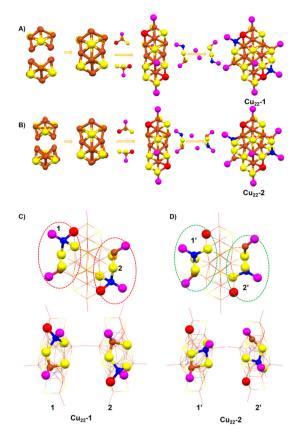


Fig. 1 The total structures of (A) Cu_{22} -1 and (B) Cu_{22} -2 from different views. Color labels: Cu = brown/blue, Se = yellow/red, P = purple, F = chartreuse, C = gray. For clarity, H atoms are omitted.



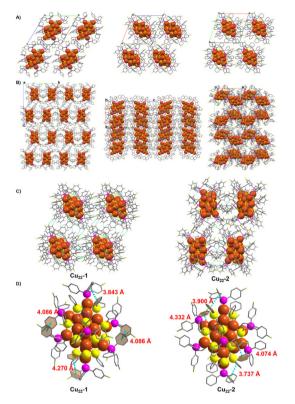


Fig. 2 (A and B) Anatomy of the two Cu₂₂ clusters. The copper atoms highlighted in blue and Se atom highlighted in red represent a slight change in bonding patterns in the surface structure. (C and D) The different bonding environments of Cu₂(SeR)₂(PR₃)₂ motifs with the Cu₁₆Se₆@Cu₂(SeR)₆(PR₃)₂ framework. Cu = brown/blue, Se = yellow/red, P = purple. For clarity, C, H and F atoms are omitted.

1 and Cu_{22} -2 clusters, which is similar to the case of $Au_{23}(C \equiv CBu')_{15}$ and different from the case of $Au_{38}(PET)_{24}$, where completely different metal cores were observed in the two isomers. The Cu-Cu distances gave an average of 2.647 Å for Cu_{22} -1 and 2.672 Å for Cu_{22} -2, while the Cu-Se distances gave an average of 2.530 Å for Cu_{22} -1 and 2.519 Å for Cu_{22} -2, and the Cu-P distances gave an average of 2.223 Å for Cu_{22} -1 and 2.228 Å for Cu_{22} -2 (Fig. S5 and 6†). Furthermore, the differences in bonding modes between the two surface Cu-P ligands and the overall framework were found to be the main cause of isomerism of the Cu_{22} -1 and Cu_{22} -2 clusters, as illustrated in Fig. S7.†

Regarding the crystal system, the two isomeric Cu_{22} -1 and Cu_{22} -2 clusters exhibit different space groups despite sharing the same crystal condition (CH₂Cl₂ and *n*-hexane). Cu_{22} -1 crystallized in the triclinic $P\bar{1}$ space group, while Cu_{22} -2 crystallized in the orthorhombic $P_{2_1}2_12_1$ space group (Tables S1 and S2†). In the crystal unit cell of Cu_{22} -1 (Fig. 3A), only one nanocluster is observed, and these nanoclusters are arranged in the same direction in the packing model. On the other hand, Cu_{22} -2 nanoclusters in the crystal unit cell are arranged in an alternating pattern (Fig. 3B, and Fig. S8†). This indicates that

Fig. 3 Views of the assembled packing of (A) Cu_{22} -1 and (B) Cu_{22} -2 viewed along the *a*, *b* and *c* axes. (C) The intermolecular forces of C-F...H-C in the isomeric Cu_{22} -1 and Cu_{22} -2. (D) The intramolecular forces of π ··· π in the isomeric Cu_{22} -1 and Cu_{22} -2. Cu = brown, Se = yellow P = purple, F = chartreuse, C = gray. For clarity, H atoms are omitted.

structural isomerism can effectively alter the stacking pattern of clusters. In the stacking pattern of Cu_{22} -1 and Cu_{22} -2, intermolecular forces such as C-F···H-C interactions are observed (Fig. 3C), with a higher occurrence in the stacking pattern of Cu_{22} -1. Furthermore, it is noteworthy that intramolecular π ··· π interactions have been identified within both isomeric forms of Cu_{22} -1 and Cu_{22} -2 (Fig. 3D). These interactions, crucial for the stabilization of molecular structures, exhibit variations that can be attributed to the differing arrangements of surface ligands across the isomers. This observation underscores the significant role that ligand positioning plays in influencing the molecular interactions and, consequently, the overall behavior of these nanoclusters. These intramolecular and intermolecular forces contribute to the efficient stability of the two isomeric Cu_{22} -1 and Cu_{22} -2 clusters.

As determined by single-crystal X-ray diffraction (SCXRD), the two isomeric Cu_{22} -1 and Cu_{22} -2 clusters were found to have the formula Cu_{22} (SePh)₁₀(Se)₆(P(Ph-⁴F)₃)₈, with a total of 22 copper atoms, 10 SePh⁻ ligands, 6 Se ligands, and 8 P(Ph-⁴F)₃ ligands. Both isomeric nanoclusters were found to possess 0 free electrons, calculated as 22 (Cu) – 10 (SePh) – 6 (Se) × 2 – 0 (charge) = 0 e. To further validate the neutral state of the cluster, as indicated by X-ray single-crystal analysis, electrospray ionization time-of-flight mass spectrometry was conducted in both positive and negative modes. No mass signal for the cluster was detected in either the positive or negative ion mode. The solubility of the Cu₂₂ clusters was tested in solvents such as toluene, CH₂Cl₂, CHCl₃, CH₃OH, CH₃CH₂OH and CH₃CN. Cu₂₂ was found to be practically insoluble in CH₃OH, CH₃CH₂OH and CH₃CN, while showing limited solubility in toluene, CH₂Cl₂ and CHCl₃. As Cu₂₂ exhibits stability for several hours in CH₂Cl₂ solution, CH₂Cl₂ was selected as the solvent for the UV-vis spectral analysis. The UV-vis spectra of Cu₂₂-1 and Cu₂₂-2 in CH₂Cl₂ are shown in Fig. 4A and B, respectively. Cu22-1 exhibited a shoulder band at 420 nm, with the optical energy gap being 2.60 eV, while Cu₂₂-2 showed a very weak shoulder band at 382 nm, with the optical energy gap being 2.73 eV (Fig. S9[†]). These distinct UV-vis spectra indicated that the two isomeric Cu₂₂-1 and Cu₂₂-2 clusters possess different electronic structures, which could potentially impact their catalytic performance. X-ray photoelectron spectroscopy (XPS) was performed to confirm the formula. XPS analysis demonstrated the Cu/Se/P atomic ratio of 22/11.8/8.3 and 22/ 12.3/8.2 for Cu₂₂-1 and Cu₂₂-2, respectively, close to the ratio of 22/12/8 obtained from the crystal analysis results. The peak signals of Cu, Se, and P are shown in Fig. 4C and D. This result illustrated that the valence state of Cu in the Cu22 nanocluster was close to +1 (Fig. S10[†]). Elemental analysis (EA) measurement (Table S3[†]) was performed and the ratio of elements agrees well with that from the X-ray crystallographic analysis. In addition, powder X-ray diffraction (PXRD) was

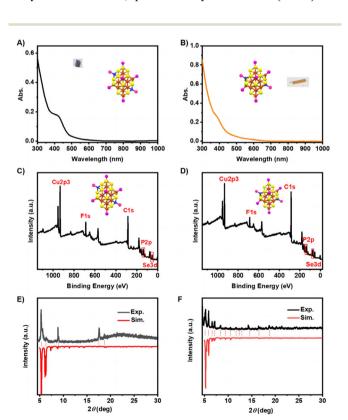


Fig. 4 The UV-vis spectra of isomeric (A) Cu_{22} -1 dissolved in CH_2Cl_2 and (B) Cu_{22} -2 slightly dissolved in CH_2Cl_2 ; the XPS data of (C) Cu_{22} -1 and (D) Cu_{22} -2; the PXRD data of (E) Cu_{22} -1 and (F) Cu_{22} -2.

used to assess the purity of the nanoclusters (Fig. 4E and F). The results show that the experimental data is in good agreement with theoretical data, which confirmed their high phase purity. Fluorescence spectroscopy was conducted on the two isomers Cu_{22} -1 and Cu_{22} -2 at low temperatures. As illustrated in Fig. S11,† it was observed that both isomers exhibited no fluorescence, whether in solution or in the solid state. Consequently, these findings categorized the two isomers of Cu_{22} -1 and Cu_{22} -2 as non-fluorescent clusters.

Furthermore, the electronic structures of isomeric Cu₂₂-1 and Cu₂₂-2 were predicted by DFT calculation.⁴⁷⁻⁵¹ As depicted in Fig. 5, comparing the partial density-of-states (PDOS) diagrams of Cu₂₂-1 and Cu₂₂-2 provides a clearer insight into the atomic distribution within these two cluster structures and their respective contributions to orbitals across different energy levels. This comparative analysis helps to uncover both similarities and distinctions in the electronic structure of the two clusters. From Fig. 5, it is evident that in the low-energy occupied orbital regions of both clusters, the pink and orange curves are relatively prominent, indicating a significant role played by the Cu and Se atoms' orbitals in forming these occupied orbitals in Cu₂₂-1 and Cu₂₂-2. Conversely, the unoccupied orbitals in the higher energy range of the clusters were predominantly composed of C atom orbitals (as shown by the red curve in the PDOS). Furthermore, the DOS diagram reveals that the disparity in the HOMO-LUMO energy gaps between Cu22-1 and Cu22-2 is minimal (2.86 eV and 2.73 eV, respectively), suggesting a similarity in their electronic structures. The HOMO-LUMO energy gaps agreed with the optical energy gap

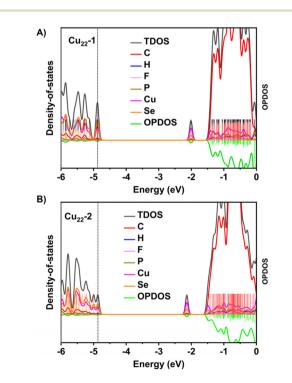


Fig. 5 Calculated PDOS for (A) Cu₂₂-1 and (B) Cu₂₂-2. Here the orbital energy range is set from -6 eV to 0 eV.

well. Nonetheless, there are subtle discrepancies in the DOS curves of the two clusters. Specifically, the TDOS curves (depicted in black) of Cu_{22} -1 and Cu_{22} -2 exhibit noticeable distinctions in the vicinity of the -5.0 eV energy level. More precisely, within this energy range, the two orbitals of Cu_{22} -1 form a distinct higher peak. Conversely, due to a significant energy gap disparity between the two orbitals in Cu_{22} -2, under the same broadening function and full width at half maximum (FWHM), the TDOS displays two shorter peaks. This implies that the orbital density in the -5.0 eV to -4.6 eV range differs between the two clusters. Furthermore, with a relative energy difference of 0.39 eV (Cu_{22} -1 exhibiting lower energy than Cu_{22} -2), it is evident that slight variances exist in the electronic structures of Cu_{22} -1 and Cu_{22} -2.

On the other hand, UV-visible absorption spectroscopy (UV-Vis) is a powerful tool to provide structural and electronic structure information, hence the UV-Vis spectra of Cu₂₂-1 and Cu22-2 simulated by the TDDFT method provide an effective way to reveal the differences in the structure and electronic structure of the two clusters. Fig. 6A and B show the simulated UV-Vis spectra of Cu₂₂-1 and Cu₂₂-2. It can be seen that the spectral curves of these two clusters have similarities but also show obvious differences. Briefly, both Cu₂₂ isomers have four similar absorption peaks, namely peak α , peak β , peak γ and peak δ . For Cu₂₂-1, the four absorption peaks of α , β , γ and δ are located at 605 nm, 485 nm, 418 nm and 366 nm, respectively. The corresponding four absorption peaks in Cu₂₂-2 are located at 623 nm, 499 nm, 402 nm and 367 nm, respectively. Therefore, the electronic structures of the two Cu₂₂ are similar to a large extent. The transition modes shown in Tables S4 and 5[†] reveal the attributions of these absorption peaks. Obviously, the peak α in the two Cu₂₂ clusters' spectra has the same attribution, and both are obtained by broadening the first excited state and the second excited state. As shown in Table S4,† for Cu_{22} -1, the first excited state is characterized by $H \rightarrow L$ contri-

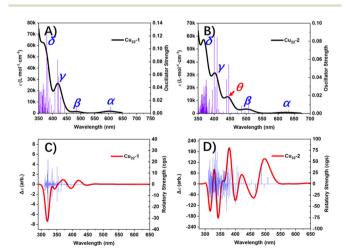
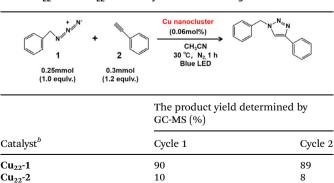


Fig. 6 Simulated UV-visible (UV-Vis) spectra and electronic circular dichroism (ECD) spectra for Cu_{22} -1 and Cu_{22} -2 based on the TDDFT method. (A and B) UV-Vis spectra of Cu_{22} -1 and Cu_{22} -2, respectively; (C and D) ECD spectra of Cu_{22} -1 and Cu_{22} -2, respectively.

buting 66.6%, followed by $H-1 \rightarrow L$ contributing 31.2%. The second excited state is characterized by an $H-1 \rightarrow L$ contribution of 66.2%, followed by an $H \rightarrow L$ contribution of 31.0%. This is very similar to the assignment of the absorption peak α in the Cu22-2 spectrum (Table S5[†]). However, Tables S5 and S6[†] show that there are obvious differences in the assignments of the absorption peaks β , γ and δ in the spectra of the two Cu₂₂ clusters. Interestingly, as shown in Fig. 6B, due to the difference in geometric structure, Cu22-2 has an additional absorption peak θ compared to Cu₂₂-1 (see Table S6[†] for its assignment). This shows that there are significant differences in the spectral characteristics of the two Cu₂₂ clusters, revealing the differences in their electronic structures. Furthermore, based on the rotatory strength from the ground state to each excited state calculated by TDDFT, we also plotted the electronic circular dichroism (ECD) spectra of the two Cu₂₂ clusters, which are shown in Fig. 6C and D. It can be clearly found that the ECD spectra of the two Cu₂₂ clusters are significantly different. The reason is that the ECD is extremely sensitive to conformation. Therefore, even if Cu22-1 and Cu22-2 only have a small difference in the shell structure, the difference can still be clearly reflected in the ECD.

The variations in surface shell ordering cause structural isomerism, altering the electronic structure, which then will influence the catalytic activity. To explore this, the copper-catalyzed [3 + 2] azide–alkyne cycloaddition (CuAAC) reaction was used as an example reaction, and the activity of Cu₂₂-1 and Cu₂₂-2 was evaluated (Table 1 and Table S6†). The reaction was conducted in acetonitrile, using 0.06 mol% of Cu₂₂-1 and Cu₂₂-2 crystals as catalysts suspended in the solvent.^{52–56} After 24 hours at 50 °C, Cu₂₂-1 achieved a product yield of 92%, while Cu₂₂-2 yielded only 36% (Table S6†). A time-dependent kinetic study of the CuAAC reaction was also performed. Cu₂₂-1 exhibited a catalytic efficiency of 64% at approximately 12 hours, whereas Cu₂₂-2 had a catalytic efficiency of 32%. With an extended reaction time, Cu₂₂-1 achieved a catalytic efficiency of 80% at approximately 18 hours and 92% at



 a Benzyl azide (0.25 mmol, 1.0 equiv.), phenylacetylene (0.3 mmol, 1.2 equiv.) and acetonitrile (2 mL). b With respect to the amount of benzyl azide.

Table 1The catalytic performance of isomeric Cu22-1 and Cu22-2. [3 +2] cycloaddition between benzyl azide and phenylacetylene using isomeric Cu22-1 and Cu22-2 as catalysts under visible light^a

approximately 24 hours (Table S6[†]). On the other hand, Cu₂₂-2 reached a catalytic efficiency of 35% at around 18 hours and 36% at around 24 hours. Additionally, due to the absorption peaks near 400 nm in both isomers, a photoinduced catalytic reaction was attempted using 405 nm blue LED irradiation. As shown in Table 1, Cu₂₂-1 achieved a product yield of 90% after only 1.0 hour of irradiation, while Cu22-2 yielded only 10%. These differences in catalytic efficiency between Cu22-1 and Cu_{22} -2 highlight how the structural isomerism, caused by the arrangement of the outer ligands, can effectively regulate the clusters' catalytic performance. TDDFT calculations indicated that the oscillator strength between the first excited state and the ground state of Cu₂₂-1 is 0.01004, while in Cu₂₂-2, this oscillator strength is only 0.00405, as evidenced by the height of the vertical line representing the lowest excited state in the spectral graph. Typically, an oscillator strength below 0.01 suggests a transition is forbidden, leading us to consider the lowest excited state of Cu22-2 as a dark state. Therefore, even though the lowest excitation energy of Cu₂₂-1 is slightly higher than that of Cu₂₂-2, the significant oscillator strength of Cu₂₂-1 facilitates the easy absorption of light at the corresponding frequency to form electron-hole pairs. This attribute makes Cu22-1 exhibit markedly better photocatalytic activity compared to Cu22-2. And as depicted in Fig. S12,† the UV-vis and P-XRD spectra demonstrate significant consistency before and after the photoinduced catalytic reaction, indicating the clusters maintain their integrity during the reaction process.

Conclusions

In summary, we have successfully synthesized and characterized two isomeric copper nanoclusters, Cu₂₂(SePh)₁₀(Se)₆(P(Ph- $(4F)_{3}_{8}-1$ (Cu₂₂-1, $P\bar{1}$) and Cu₂₂(SePh)₁₀(Se)₆(P(Ph-⁴F)₃)₈-2 (Cu₂₂-2, P2₁2₁2₁), using SCXC. Cu₂₂(SePh)₁₀(Se)₆(P(Ph-⁴F)₃)₈ contains a Cu₁₆Se₆ core formed by the fusion of two distorted Ino decahedron Cu₁₀Se₃ clusters through the sharing of four Cu atoms. This $Cu_{16}Se_6$ core is further capped by two $Cu(SeR)_3(PR_3)$ motifs, two Cu(SeR)₂(PR₃)₂ motifs and two PR₃ phosphine ligands. The isomerism of Cu_{22} -1 and Cu_{22} -2 is due to the different arrangements of the surface motifs, which result in differences in electronic structure (as manifested by different UV absorption spectra, and DFT calculation) and catalytic efficiency in the copper-catalyzed [3 + 2] azide-alkyne cycloaddition (CuAAC). The clusters are highly stable due to $\pi \cdots \pi$ intramolecular interactions and C-F--H-C intermolecular forces, making them difficult to dissolve. These two isomeric copper nanoclusters enrich the development of structural isomerism in copper nanoclusters and provide an opportunity to investigate the structure-function relationship.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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References

- 1 X. Wang, B. Yin, L. Jiang, C. Yang, G. Zou, S. Chen and M. Zhu, *Science*, 2023, **381**, 784–790.
- 2 W. Gao, Q. Li, W. Zhong, X. Zhou, Y. Ge, Q. Yan and L. Shang, *Chem. Eng. J.*, 2023, **456**, 140982.
- 3 X. Ma, J. Li, P. Luo, J. Hu, Z. Han, X. Dong, G. Xie and S. Zang, *Nat. Commun.*, 2023, **14**, 4121.
- 4 X. Hu, H. Cao, W. Dong and J. Tang, *Talanta*, 2021, 233, 122480.
- 5 M. Wang, J. Zhang, X. Zhou, H. Sun and X. Su, *Sens. Actuators, B*, 2022, **358**, 131488.
- 6 Q. Xue, Z. Wang, S. Han, Y. Liu, X. Dou, Y. Li, H. Zhu and X. Yuan, *J. Mater. Chem. A*, 2022, **10**, 8371–8377.
- 7 Q. Wu, D. Si, P. Sun, Y. Dong, S. Zheng, Q. Chen, S. Ye, D. Sun, R. Cao and Y. Huang, *Angew. Chem., Int. Ed.*, 2023, 62, e2023068.
- 8 S. Zhuang, D. Chen, W. Fan, J. Yuan, L. Liao, Y. Zhao, J. Li, H. Deng, J. Yang, J. Yang and Z. Wu, *Nano Lett.*, 2022, 22, 7144–7150.
- 9 L. Liu, Z. Wang, Z. Wang, R. Wang, S. Zang and T. C. W. Mak, *Angew. Chem., Int. Ed.*, 2022, **61**, e2022056.
- 10 Z. Guan, F. Hu, J. Li, Z. Wen, Y. Lin and Q. Wang, J. Am. Chem. Soc., 2020, 142, 2995–3001.
- H. Yi, K. M. Osten, T. I. Levchenko, A. J. Veinot, Y. Aramaki,
 T. Ooi, M. N. Nambo and C. M. Crudden, *Chem. Sci.*, 2021,
 12, 10436–10440.
- 12 Y. Chen, C. Liu, Q. Tang, C. Zeng, T. Higaki, A. Das, D. Jiang, N. L. Rosi and R. Jin, *J. Am. Chem. Soc.*, 2016, **138**, 1482–1485.
- S. Horiuchi, S. Moon, A. Lto, J. Tessarolo, E. S. Y. Arikawa,
 G. H. Clever and K. Umakoshi, *Angew. Chem., Int. Ed.*, 2021,
 60, 10654–10660.
- 14 S. Zhuang, L. Liao, M. Li, C. Yao, Y. Zhao, H. Dong, J. Li,
 H. Deng, L. Lie and Z. Wu, *Nanoscale*, 2017, 9, 14809–14813.
- 15 Y. T. Cao, S. Malola, M. F. Matus, T. K. Chen, Q. F. Yao, R. Shi, H. Häkkinen and J. P. Xie, *Chem*, 2021, 7, 2227– 2244.
- 16 Y. Li, X. Luo, P. Luo, Q. Zang, Z. Wang and S. Zang, ACS Nano, 2023, 17, 5834–5841.
- 17 S. Knoppe and T. Bürgi, Acc. Chem. Res., 2014, 47, 1318– 1326.

- 18 W. Yu, D. Hu, L. Xiong, Y. Li, X. Kang, S. Chen, S. Wang, Y. Pei and M. Zhu, *Part. Part. Syst. Charact.*, 2019, 36, 1800494.
- 19 S. Yamazoe, S. Matsuo, S. Muramatsu, S. Takano, K. Nitta and T. Tsukuda, *Inorg. Chem.*, 2017, **56**, 8319–8325.
- 20 N. Xia, J. Yuan, L. Liao, W. Zhang, J. Li, H. Deng, J. Yang and Z. Wu, *J. Am. Chem. Soc.*, 2020, **142**, 12140–12145.
- 21 X. Liu, W. Xu, X. Huang, E. Wang, X. Cai, Y. Zhao, J. Li, M. Xiao, C. Zhang, Y. Gao, W. Ding and Y. Zhu, *Nat. Commun.*, 2020, **11**, 3349.
- 22 S. Tian, Y. Li, M. Li, J. Yuan, J. Yang, Z. Wu and R. Jin, *Nat. Commun.*, 2015, **6**, 8667.
- 23 S. Zhuang, L. Liao, J. Yuan, N. Xia, Y. Zhao, C. Wang, Z. Gan, N. Yan, L. He, J. Li, H. Deng, Z. Guan, J. Yang and Z. Wu, *Angew. Chem., Int. Ed.*, 2019, **58**, 4510–4514.
- 24 Y. Zhang, A. Tang, X. Cai, J. Xu, G. Li, W. Hu, X. Liu, M. Chen and Y. Zhu, *Nano Res.*, 2023, 16, 3641–3648.
- 25 S. Chen, L. Xiong, S. Wang, Z. Ma, S. Jin, H. Sheng, Y. Pei and M. Zhu, *J. Am. Chem. Soc.*, 2016, **138**, 10754–10757.
- 26 S. Yang, J. Chai, Y. Song, J. Fan, T. Chen, S. Wang, H. Yu, X. Li and M. Zhu, J. Am. Chem. Soc., 2017, 139, 5668–5671.
- 27 Y. Song, S. Wang, J. Zhang, X. Kang, S. Chen, P. Li, H. Sheng and M. Zhu, *J. Am. Chem. Soc.*, 2014, **136**, 2963– 2965.
- 28 A. Das, T. Li, G. Li, K. Nobusada, C. Zeng, N. L. Rosi and R. Jin, *Nanoscale*, 2014, 6, 6458–6462.
- 29 S. Jin, F. Xu, W. Du, X. Kang, S. Chen, J. Zhang, X. Li, D. Hu, S. Wang and M. Zhu, *Inorg. Chem.*, 2018, 57, 5114–5119.
- 30 C. Zeng, T. Li, A. Das, N. L. Rosi and R. Jin, J. Am. Chem. Soc., 2013, 135, 10011–10013.
- 31 Y. Bao, X. Wu, B. Yin, X. Kang, Z. Lin, H. Deng, H. Yu, S. Jin, S. Chen and M. Zhu, *Chem. Sci.*, 2022, **13**, 14357– 14365.
- 32 A. Dass, T. Jones, M. Rambukwella, D. Crasto, K. J. Gagnon,
 L. Sementa, M. D. Vetta, O. Baseggio, E. Aprà, M. Stener and A. Fortunelli, *J. Phys. Chem. C*, 2016, 120, 6256–6261.
- 33 T. Higaki, C. Liu, C. Zeng, R. Jin, Y. Chen, N. L. Rosi and R. Jin, *Angew. Chem., Int. Ed.*, 2016, 55, 6694–6697.
- 34 R. S. Dhayal, Y. Lin, J.-H. Liao, Y.-J. Chen, Y.-C. Liu, M.-H. Chiang, S. Kahlal, J. Y. Saillard and C. Liu, *Chem. – Eur. J.*, 2016, 22, 9943–9947.
- 35 M. W. Heaven, A. Dass, P. S. White, K. M. Holt and R. W. Murray, J. Am. Chem. Soc., 2008, 130, 3754–3755.
- 36 M. Zhu, C. M. Aikens, F. J. Hollander, G. C. Schatz and R. Jin, J. Am. Chem. Soc., 2008, 130, 5883–5885.
- 37 J. Li, Z. Guan, Z. Lei, F. Hu and Q. Wang, Angew. Chem., Int. Ed., 2019, 58, 1083–1087.

- 38 N. Yan, N. Xia, L. Liao, M. Zhu, F. Jin, R. Jin and Z. Wu, *Sci. Adv.*, 2018, 4, eaat7259.
- 39 Z. Lei, J. Li, X.-K. Wan, W.-H. Zhang and Q.-M. Wang, Angew. Chem., Int. Ed., 2018, 57, 8639–8643.
- 40 R. S. Dhayal, J.-H. Liao, X. Wang, Y.-C. Liu, M.-H. Chiang,
 S. Kahlal, J.-Y. Saillard and C. W. Liu, *Angew. Chem., Int. Ed.*, 2015, 54, 13604–13608.
- 41 C. K. Zhang, Z. Wang, W.-D. Si, L. Y. Wang, J.-M. Dou, Z.-Y. Gao, C.-H. Tung and D. Sun, ACS Nano, 2022, 16, 9598–9607.
- 42 T. Higaki, C. Liu, M. Zhou, T. Luo, N. L. Rosi and R. Jin, J. Am. Chem. Soc., 2017, 139, 9994–10001.
- 43 B. Yan, X. You, X. Tang, J. Sun, Q. Xu, L. Wang, Z.-J. Guan,
 F. Li and H. Shen, *Chem. Mater.*, 2024, 36, 1004–1012.
- 44 O. Fuhr, A. Meredith and D. Fenske, J. Chem. Soc., Dalton Trans., 2002, 4091–4094.
- 45 R. Langer, L. Wünsche, D. Fenske and O. Fuhr, Z. Anorg. Allg. Chem., 2009, 635, 2488–2494.
- 46 R. Langer, W. Yu, L. Wünsche, G. Buth, O. Fuhr and D. Fenske, Z. Anorg. Allg. Chem., 2011, 637, 1834–1840.
- 47 H. Li, P. Wang, C. Zhu, W. Zhang, M. Zhou, S. Zhang, C. Zhang, Y. Yun, X. Kang, Y. Pei and M. Zhu, *J. Am. Chem. Soc.*, 2022, **144**, 23205–23213.
- 48 M. Cui, Y. Shi, X. Ma, Q. Li, L. Chen, L. Zhang, J. Wu, H. Yu and M. Zhu, ACS Nano, 2024, 18, 6591–6599.
- 49 G. Luo, Z. Pan, B. Han, G. Dong, C. Deng, M. Azam, Y. Tao, J. He, C. Sun and D. Sun, *Angew. Chem., Int. Ed.*, 2023, 62, e2023068.
- 50 Z. Wang, Y. Zhu, O. Ahlstedt, K. Konstantinou, J. Akola, C. Tung, F. Alkan and D. Sun, *Angew. Chem., Int. Ed.*, 2024, 63, e20231451.
- 51 T. Jia, Z. Guan, C. Zhang, X. Zhu, Y. Chen, Q. Zhang, Y. Yang and D. Sun, *J. Am. Chem. Soc.*, 2023, **145**, 10355– 10363.
- 52 D. Campeau, A. Pommainville, M. Gorodnichy and F. Gagosz, J. Am. Chem. Soc., 2023, 145, 19018–19029.
- 53 W. D. G. Brittain, B. R. Buckley and J. S. Fossey, ACS Catal., 2016, 6, 3629–3636.
- 54 J. M. Holub and K. Kirshenbaum, Chem. Soc. Rev., 2010, 39, 1325–1337.
- 55 C. Dong, R. Huang, A. Sagadevan, P. Yuan, L. G. Arzaluz, A. Ghosh, S. Nematulloev, B. Alamer, O. M. Mohammed, I. Hussain, M. Rueping and O. M. Bakr, *Angew. Chem., Int. Ed.*, 2023, **62**, e20230714.
- 56 Y. Fang, K. Bao, P. Zhang, H. Sheng, Y. Yun, S. Hu, D. Astruc and M. Zhu, *J. Am. Chem. Soc.*, 2021, 143, 1768– 1772.