



Cite this: *Chem. Sci.*, 2025, **16**, 20389

All publication charges for this article have been paid for by the Royal Society of Chemistry

Dynamic structural engineering of ferrocene-functionalized Ag_{20} nanoclusters for enhanced CO_2 electroreduction performance

Hong-Yan Zhu,^a Xiao-Wei Wang,^a Xin-Yu Chen,^a Lan-Yan Li,^b Yi-Xin Li,^c Wei Dong Yu,^b Jun Yan^a and Chao Liu^a     

The integration of organometallic motifs with metal nanoclusters offers a powerful strategy for constructing hybrid catalysts with precisely tunable active sites. Here, we report the synthesis of a 20-silver nanocluster, $\text{Ag}_{20}\text{-Fc}$, via cooperative coordination between thiocalix[4]arene (TC4A) and ferrocenylacetylene ligands. The cluster adopts a distinctive sandwich-like architecture, featuring two $\text{Ag}_5\text{@TC4A}$ units flanking a ferrocenyl-stabilized Ag_{10} core, and exhibits excellent structural tunability. Ligand engineering allows replacement of the ferrocenylacetylene units with methoxyphenylacetylene ($\text{Ag}_{20}\text{-OPh}$) or phenylacetylene ($\text{Ag}_{20}\text{-Ph}$), while preserving the core framework. Electrospray ionization mass spectrometry reveals dynamic structural reorganization in solution, where $\text{Ag}_5\text{@TC4A}$ fragments are capable of capturing Ag–alkyne species and reassembling into sandwich-type clusters—a process substantiated by the structural features of Ag_{24} , Ag_{12} , and $\text{Cu}_2\text{Ag}_{11}$. $\text{Ag}_{20}\text{-Fc}$ generates a locally electron-rich environment and conjugated ethynyl bridges that facilitate directional charge transfer, delivering outstanding electrocatalytic CO_2 reduction. It achieves over 98% faradaic efficiency for CO across a wide potential range (−1.0 to −1.8 V vs. RHE) and maintains operational stability for 24 h, significantly outperforming $\text{Ag}_{20}\text{-OPh}$ and $\text{Ag}_{20}\text{-Ph}$. Density functional theory calculations uncover a dual enhancement mechanism in which orbital hybridization between ferrocenyl groups and silver atoms tunes the electronic structure at active sites, resulting in a 0.28 eV reduction in the energy barrier for *COOH intermediate formation compared to $\text{Ag}_{20}\text{-Ph}$.

Received 18th August 2025
Accepted 27th September 2025

DOI: 10.1039/d5sc06306j
rsc.li/chemical-science

Introduction

The electrochemical reduction of carbon dioxide (e CO_2 RR) has emerged as a promising carbon-neutral strategy, garnering increasing attention for its dual potential to mitigate greenhouse gas emissions and rebalance the carbon cycle *via* renewable electricity.^{1–3} This reaction enables the conversion of CO_2 into value-added fuels and chemicals under ambient conditions, offering significant potential for sustainable energy and chemical production.^{4–9} Despite this promise, practical deployment of e CO_2 RR remains hindered by several key challenges: the thermodynamic stability and chemical inertness of CO_2 , competing hydrogen evolution reaction (HER), and the complexity of selectively controlling multi-electron, multi-proton transfer pathways.^{10–15}

To address these limitations, extensive efforts have been dedicated to developing advanced electrocatalysts capable of achieving high faradaic efficiencies, industrially relevant current densities, and long-term operational durability.^{16–21} Among these, nanocatalysts with atomically defined structures have demonstrated significant potential in tuning catalytic activity and selectivity.^{22–29} However, the bottom-up synthesis of such catalysts with precise control over size, geometry, and elemental composition remains a formidable challenge, emphasizing the need for innovative synthetic strategies.^{30–32} In this context, ligand-protected metal nanoclusters (NCs), typically <3 nm in diameter, have emerged as a unique class of atomically precise materials situated at the interface between molecular and nanoscale domains.^{33–40} These well-defined “superatoms” offer distinct advantages for catalytic applications, including atomic-level structural resolution *via* single-crystal X-ray diffraction (SCXRD), tailorabile surface environments through ligand engineering, and hybrid electronic states originating from strong metal-ligand orbital coupling.^{41–47} These features make NCs an ideal platform for probing structure–activity relationships and for the rational design of next-generation electrocatalysts.

^aCollege of Chemistry and Chemical Engineering, Central South University, Changsha 410083, Hunan, P. R. China. E-mail: chaoliu@csu.edu.cn

^bSchool of Resources and Environment, Hunan University of Technology and Business, Changsha 410000, P. R. China

^cKey Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Nankai University, Tianjin 300071, China

^dState Key Laboratory of Structural Chemistry, P. R. China



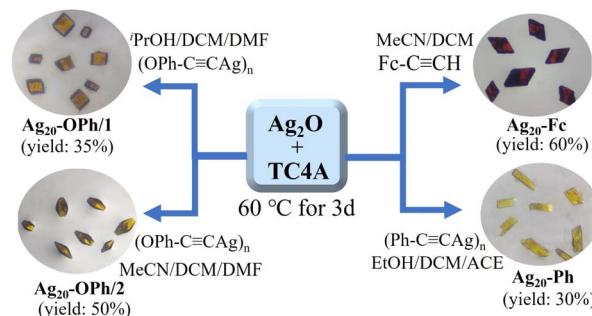
A critical requirement for efficient eCO_2RR is rapid and effective charge transport across the catalyst–electrode interface.⁴⁸ However, the insulating nature of traditional ligands used to stabilize NCs often impedes electron transfer, thereby compromising catalytic efficiency. To address this limitation, redox-active ligands such as metallocenes—particularly ferrocene and its derivatives—have emerged as promising molecular components.⁴⁹ These organometallic units exhibit outstanding redox reversibility, fast electron-transfer kinetics, and well-defined electrochemical properties. When integrated into NCs, metallocenes not only facilitate electronic communication between active sites and electrodes but also offer a means to modulate the structural and electronic configuration of the catalyst.^{50–53} Nevertheless, the incorporation of metallocene moieties into atomically precise NCs remains underexplored, primarily due to the synthetic complexity and structural heterogeneity of conventional nanoparticle surfaces, which hinder atomic-level mechanistic understanding.

Herein, we report the design of a hybrid nanocatalyst, $\text{Ag}_{20}\text{-Fc}$, constructed by anchoring twelve ferrocenylacetylene ligands onto a thiocalix[4]arene (TC4A)-stabilized silver nanocluster. This atomically defined framework allows systematic investigation of ligand effects at the molecular level. Targeted ligand engineering further affords two analogues, $\text{Ag}_{20}\text{-OPh}$ and $\text{Ag}_{20}\text{-Ph}$, by replacing ferrocenyl units with methoxyphenylacetylene and phenylacetylene, respectively, while preserving the Ag_{20} core. Solution-phase electrospray ionization mass spectrometry (ESI-MS) revealed dynamic self-assembly behavior of the Ag_{20} motif, wherein two $\text{Ag}_5@\text{TC4A}$ fragments capture Ag–alkyne species and reorganize into sandwich-like architectures *via* well-defined intermediates. This structural adaptability underscores the modularity of the cluster framework and its suitability for mechanistic studies. Electrochemical characterization revealed a pronounced dependence of catalytic performance on the nature of surface ligands. Among the series, $\text{Ag}_{20}\text{-Fc}$ exhibited superior electrocatalytic activity for CO_2 reduction, achieving a CO faradaic efficiency (FE) exceeding 98% over a wide potential window (−1.0 to −1.8 V *vs.* RHE) and demonstrating operational stability for over 24 hours. In contrast, both $\text{Ag}_{20}\text{-OPh}$ and $\text{Ag}_{20}\text{-Ph}$ displayed lower CO selectivity, with maximum FEs of ~91%. Density functional theory (DFT) calculations elucidated an enhancement mechanism in $\text{Ag}_{20}\text{-Fc}$: strong orbital hybridization between the ferrocenyl ligands and the silver core effectively modulates the local electronic structure, thereby reducing the energy barrier for ${}^*\text{OCHO}$ intermediate formation by 0.28 eV compared to $\text{Ag}_{20}\text{-Ph}$. These findings highlight the critical role of redox-active organometallic ligands in tuning both geometric and electronic properties at the active sites. Overall, this study establishes a rational design strategy that leverages organometallic ligand engineering to precisely tailor the surface and electronic environment of atomically defined nanoclusters, providing a powerful platform for the development of efficient and tunable electrocatalysts for CO_2 reduction.

Results and discussion

Synthesis and structure of $\text{Ag}_{20}\text{-Fc}$ nanocluster $\text{Ag}_{20}\text{-Fc}$ was synthesized *via* a one-pot solvothermal method by dissolving ferrocenylacetylene ($\text{Fc-C}\equiv\text{CH}$), Ag_2O , and TC4A in a $\text{CH}_3\text{CN}/\text{CH}_2\text{Cl}_2$ mixed solvent (Scheme 1). The solution was heated at 60 °C for 72 hours, resulting in the direct precipitation of yellow crystalline $\text{Ag}_{20}\text{-Fc}$ with a yield of 62%. SCXRD analysis revealed that $\text{Ag}_{20}\text{-Fc}$ crystallizes in the monoclinic system with space group $C2/c$, containing one cluster per unit cell. The molecular formula $\{\text{Ag}_{20}(\text{TC4A})_2(\text{Fc-C}\equiv\text{C})_{12}\}$ indicates an architecture composed of 20 Ag atoms, two TC4A ligands, and twelve ferrocene-alkynyl groups. The cluster adopts a sandwich-like prismatic structure (Fig. 1A), featuring two $\{\text{Ag}_5@\text{TC4A}\}$ caps flanking a central Ag_{10} core stabilized by ferrocene-alkynyl ligands. Each TC4A ligand coordinates in a $\mu_5\text{-}\kappa(\text{O})^3\text{-}\kappa(\text{O})^3\text{-}\kappa(\text{O})^3\text{-}\kappa(\text{S})^1\text{-}\kappa(\text{S})^1\text{-}\kappa(\text{S})^1$ binding mode, encapsulating a Ag_5 unit (Fig. 1B). Four Ag^+ form a distorted square at the lower rim of TC4A, while an additional Ag^+ resides at the ligand's upper rim, secured by four $\text{Ag}-\text{O}$ bonds and weak $\text{Ag}\cdots\text{Ag}$ interactions (2.976(5)–3.047(7) Å). The Ag_{10} core exhibits a layered sandwich configuration (Fig. 1C), comprising a central Ag_4 planar square intersected by two perpendicular Ag_3 linear units. The $\text{Ag}\cdots\text{Ag}$ distances within the Ag_{10} core range from 2.783(3) to 2.808(4) Å, consistent with argentophilic interactions (Fig. 1D). Twelve alkyne ligands bridge the Ag_{10} core and $\{\text{Ag}_5@\text{TC4A}\}$ subunits (Fig. 1E), consolidating the cluster's cross-shaped geometry with C_{2v} symmetry.

Ligand Engineering of Ag_{20} nanoclusters subtle modulation of ligand environments in Ag NCs can have profound effects on their physicochemical and catalytic properties.^{49,50} However, direct structure–property comparisons between NCs with identical metal cores but distinct surface ligands remain scarce. To probe the influence of ferrocene-based ligands on cluster performance, we synthesized three analogues—one $\text{Ag}_{20}\text{-Ph}$ (Fig. 2A) and two $\text{Ag}_{20}\text{-OPh}$ (Fig. 2B and C)—by substituting ferrocenylacetylene with phenylacetylene ($\text{Ph-C}\equiv\text{CH}$) and *para*-methoxyphenylacetylene ($\text{OPh-C}\equiv\text{CH}$), respectively. Both derivatives were obtained through careful solvent system optimization and found to be isostructural with $\text{Ag}_{20}\text{-Fc}$. Structural analysis confirmed that all three clusters preserve a nearly identical Ag_{20} core, with the primary differences residing in the



Scheme 1 Schematic illustration of the synthesis of the reported Ag_{20} clusters.



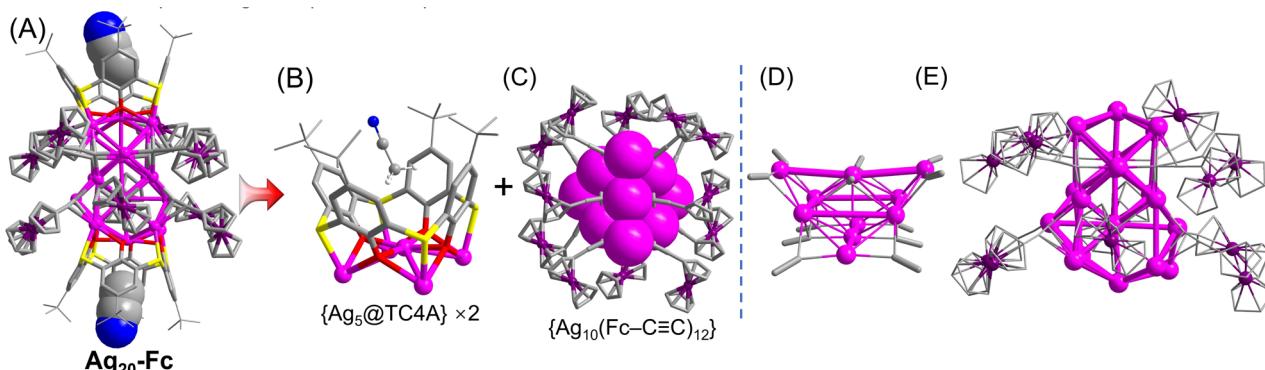


Fig. 1 Crystal structure of the $\text{Ag}_{20}\text{-Fc}$ cluster. (A) Overall molecular structure; (B) structure of the $\{\text{Ag}_5\text{(TC4A)}\}_2$ secondary building unit (SBU); (C) $\text{Ag}_{10}\text{L}_{12}$ structural unit; (D) Ag_{10} core; (E) Ag_{20} metallic core.

electronic and steric nature of the terminal alkynyl ligands (Fig. 2D and E). Interestingly, variations were observed in the guest solvent molecules encapsulated within the TC4A cavities. In $\text{Ag}_{20}\text{-Fc}$ and $\text{Ag}_{20}\text{-OPh/2}$, two CH_3CN molecules are hosted in the cavities, stabilized by $\text{C-H}\cdots\pi$ interactions with methyl groups oriented toward the cavity center. In contrast, $\text{Ag}_{20}\text{-Ph}$ and $\text{Ag}_{20}\text{-OPh/1}$ encapsulate CH_2Cl_2 and isopropanol, respectively. These guest-dependent differences induce varying degrees of distortion in the cluster frameworks. Notably, the two structural isomers of $\text{Ag}_{20}\text{-OPh}$ exhibit significant conformational disparities in their Ag cores, attributed to the steric and electronic differences between CH_3CN and isopropanol within the TC4A host. These results highlight the sensitivity of cluster conformation to host-guest interactions.

Dynamic structural transformation and modular reorganization of the Ag_{20} cluster in solution the Ag_{20} cluster can be structurally described as a modular assembly composed of two $\{\text{Ag}_5\text{(TC4A)}\}$ units bridged by a central $\text{Ag}_{10}\text{L}_{12}$ substructure. The Ag_{10} core adopts a sandwich-like configuration, with a planar Ag_4 square flanked by two perpendicular linear Ag_3 units. Understanding the behavior of such a delicate architecture in solution is crucial for elucidating its self-assembly mechanism and evaluating its structural adaptability. To explore the

dynamic nature of Ag_{20} in solution, three cluster variants— $\text{Ag}_{20}\text{-Fc}$, $\text{Ag}_{20}\text{-OPh}$, and $\text{Ag}_{20}\text{-Ph}$ —were dissolved in CHCl_3 and analyzed by ESI-MS in positive-ion mode. Notably, no intact molecular ion was observed for $\text{Ag}_{20}\text{-Fc}$, likely due to the destabilizing steric effects of the bulky ferrocenyl ligands (Fig. 3A). In contrast, $\text{Ag}_{20}\text{-OPh}$ exhibited a well-resolved peak at $m/z = 5467.08$, in excellent agreement with the calculated mass of $\{\text{HAg}_{20}(\text{TC4A})_2(\text{OPh-C}\equiv\text{C})_{12}(\text{CHCl}_3)_2(\text{MeOH})_2\}^+$ ($m/z = 5467.00$). Meanwhile, $\text{Ag}_{20}\text{-Ph}$ displayed a distinct peak at $m/z = 4805.95$, which closely matches the calculated mass of $\{\text{HAg}_{20}(\text{TC4A})_2(\text{Ph-C}\equiv\text{C})_{12}\}^+$ ($m/z = 4805.90$). These results suggest that smaller ligands enhance the solution-phase stability of the cluster.

Despite differences in overall stability, all three Ag_{20} variants exhibited similar fragmentation behavior upon ESI-MS analysis. In the m/z 2000–3000 range, signals corresponding to $\{\text{Ag}_9(\text{TC4A}) \pm (\text{AgL})_x\}^+$ species were observed, while larger fragments such as $\{\text{Ag}_{12}(\text{TC4A})_2 \pm (\text{AgL})_x\}^+$ appeared in the 3000–4000 range. These species, retaining one or two TC4A units, undergo systematic addition or loss of silver atoms and alkynyl ligands, indicative of a stepwise dissociation process. Combined with solid-state structural data, these observations reveal that Ag_{20} is intrinsically dynamic in solution—capable of

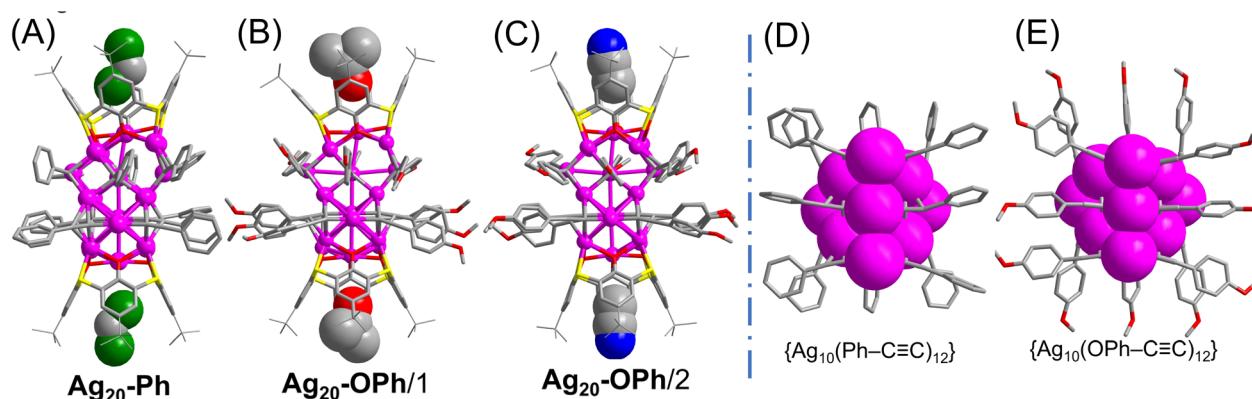


Fig. 2 Overall molecular structures of $\text{Ag}_{20}\text{-Ph}$ (A), $\text{Ag}_{20}\text{-OPh/1}$ (B), and $\text{Ag}_{20}\text{-OPh/2}$ (C); Ag_{10} core protected by phenylacetylene (D) and by *p*-methoxyphenylacetylene (E).



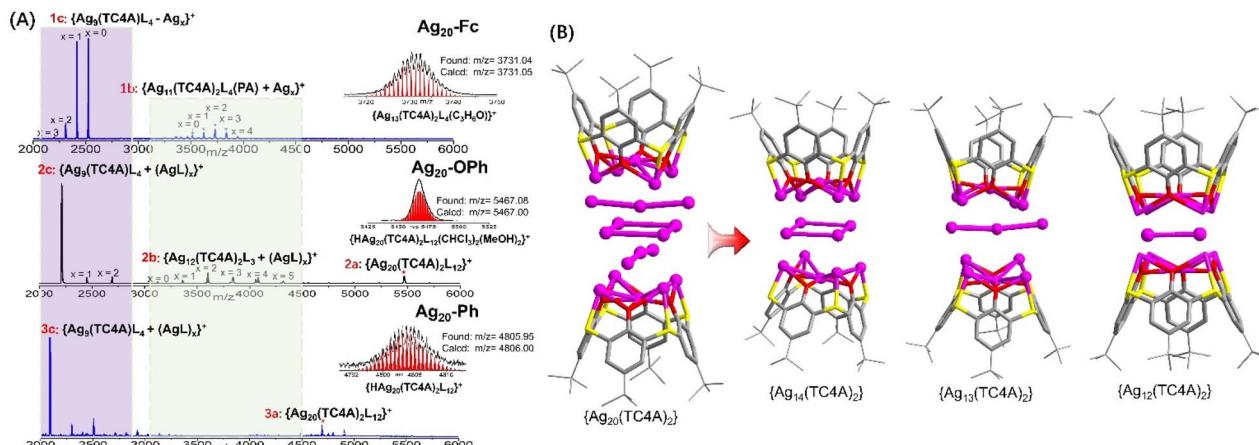


Fig. 3 (A) Positive-mode ESI-MS spectra of Ag₂₀-Fc, Ag₂₀-OPh and Ag₂₀-Ph in CH₂Cl₂ solution; (B) proposed structural disassembly pathway of the Ag₂₀ cluster.

reversible dissociation into modular units such as {Ag₅(TC4A)}, followed by reassembly into higher-order architectures (Fig. 3B). This reversible, modular behavior underscores the hierarchical and adaptive character of Ag₂₀ self-assembly in solution.

The dynamic reconfigurability of Ag₂₀ is further supported by a series of structurally related clusters synthesized under comparable conditions. Clusters such as Ag₁₂, Cu₂Ag₁₁, and Ag₂₄—all assembled from TC4A and alkynyl ligands—can be rationalized as solution-phase transformation products of Ag₂₀ through selective reorganization. For example, replacing ferrocenylacetylene with the less bulky *tert*-butylacetylene produces Ag₁₂, which retains the {Ag₅(TC4A)} fragments while simplifying the core into an Ag₂L₄ dimer (Fig. 4A). Cu₂Ag₁₁ preserves the overall sandwich-like motif of Ag₂₀ but replaces the two {Ag₅(TC4A)} caps with {CuAg₄(TC4A)} units and reorganizes the Ag₃-Ag₄-Ag₃ core into a linear Ag₃ bridge (Fig. 4B). Ag₂₄, stabilized by trifluoromethylphenylacetylene ligands, displays an even more intricate structure, featuring a planar Cl₂@Ag₉ core surrounded by three {Ag₅@TC4A} units arranged in trigonal symmetry (Fig. 4C). The Cl₂@Ag₉ motif consists of two Ag₅ pentagons sharing a common vertex, each embedding a Cl⁻ ion (Fig. 4D), with the anionic templates playing a pivotal role in directing geometric rearrangement and inducing symmetry

transformation relative to Ag₂₀ (Fig. 4E). Together, these clusters—Ag₁₂, Cu₂Ag₁₁, and Ag₂₄—serve as structural snapshots of the Ag₂₀ cluster's intrinsic dynamic and modular nature in solution. They demonstrate Ag₂₀'s capacity for reversible fragmentation and structural reorganization in response to variations in ligand identity, anionic templating, and solvent environment, highlighting its role not as a static species, but as a highly adaptive scaffold capable of tunable, hierarchical assembly.

Electrochemical CO₂ reduction Surface ligands are central to engineering the catalytic microenvironment and enhancing activity through multiple pathways.^{54,55} Nonetheless, the multivariate synergistic interactions and generalizable design principles underlying ligand modulation remain elusive. Atomically precise metal clusters, with their well-defined structures and uniform active sites, represent ideal platforms for systematically dissecting these effects. In this study, the three Ag₂₀ NCs with an identical metal core but distinct organic ligand shells were employed as a structurally controlled platform to investigate the influence of ligand engineering—specifically, organometallic functionalization—on the eCO₂RR. This model system provides unique insight into how surface chemistry affects the activity and selectivity of ultrasmall metal

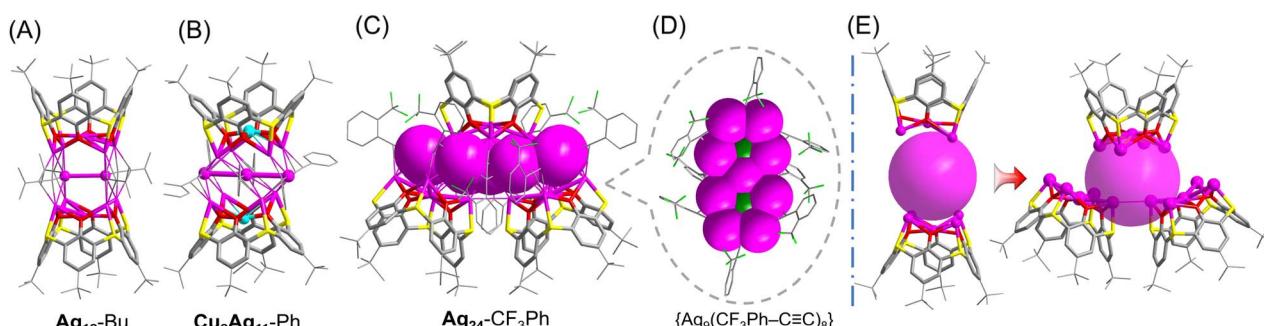


Fig. 4 Structures of the Ag₁₂ (A), Cu₂Ag₁₁ (B), and Ag₂₄ (C) clusters; (D) Cl₂@Ag₉L₈ structural motif; (E) topological structural transformations from Ag₂₀ to Ag₂₄.

catalysts. The CO₂RR performance of the clusters was initially assessed using a flow cell setup. Linear sweep voltammetry (LSV) measurements were conducted in CO₂- and N₂-saturated 1 M KOH solutions to evaluate the intrinsic catalytic activity. As shown in Fig. 5A, all three Ag₂₀ NCs exhibited substantially higher current densities and more positive onset potentials under CO₂-saturated conditions compared to N₂-saturated electrolytes, confirming their effective CO₂ reduction capabilities. Notably, Ag₂₀-Fc delivered consistently higher current densities across the entire potential window, indicating superior CO₂RR kinetics and overall catalytic performance.

Gas chromatography (GC) analysis revealed that CO and H₂ were the only gaseous products formed during electrochemical CO₂ reduction, with no detectable liquid-phase products observed *via* ¹H NMR spectroscopy. This indicates a highly selective two-electron reduction pathway. All three Ag₂₀-based NCs demonstrated excellent selectivity toward CO, consistently achieving faradaic efficiencies (FE_{CO}) above 84% over a wide potential range (−0.6 to −1.8 V vs. RHE), underscoring the intrinsic activity of the Ag₂₀ core for CO₂ electroreduction (Fig. 5B–D). However, the nature of the surface ligands had a pronounced impact on catalytic performance. Ag₂₀-Fc, functionalized with ferrocenylacetylene, exhibited the highest selectivity, maintaining FE_{CO} values above 98% from −1.0 to

−1.8 V, with a peak efficiency of 98.68% (Fig. 5E). In contrast, Ag₂₀-Ph and Ag₂₀-OPh (structure 2, containing CH₃CN molecules), modified with phenyl- and methoxyphenyl-acetylene ligands, showed lower maximum efficiencies, both remaining below 91%. Further insights were obtained by examining the CO partial current density (J_{CO}). At −1.8 V, Ag₂₀-Fc delivered a high J_{CO} of 157.54 mA cm^{−2}, far outperforming Ag₂₀-Ph (91.13 mA cm^{−2}) and Ag₂₀-OPh (73.50 mA cm^{−2}) (Fig. 5F). This enhancement highlights the role of the ferrocene moiety in promoting interfacial charge transfer, thereby improving catalytic efficiency. The turnover frequency (TOF) results corroborate these findings—Ag₂₀-Fc consistently exhibited higher TOF values across all applied potentials, confirming its superior intrinsic activity (Fig. 5G). To understand the origin of this enhanced performance, electrochemical impedance spectroscopy (EIS) was performed. Nyquist plots showed that Ag₂₀-Fc possesses lower charge transfer resistance than its counterparts, reflecting more efficient electron transport (Fig. S40). In addition, measurements of the electrochemically active surface area (ECSA) revealed a higher density of accessible active sites for Ag₂₀-Fc (Fig. S37–S39). These results collectively demonstrate that the unique electronic environment created by ferrocene ligands enhances both charge transport and active-site availability, leading to markedly improved CO₂ reduction

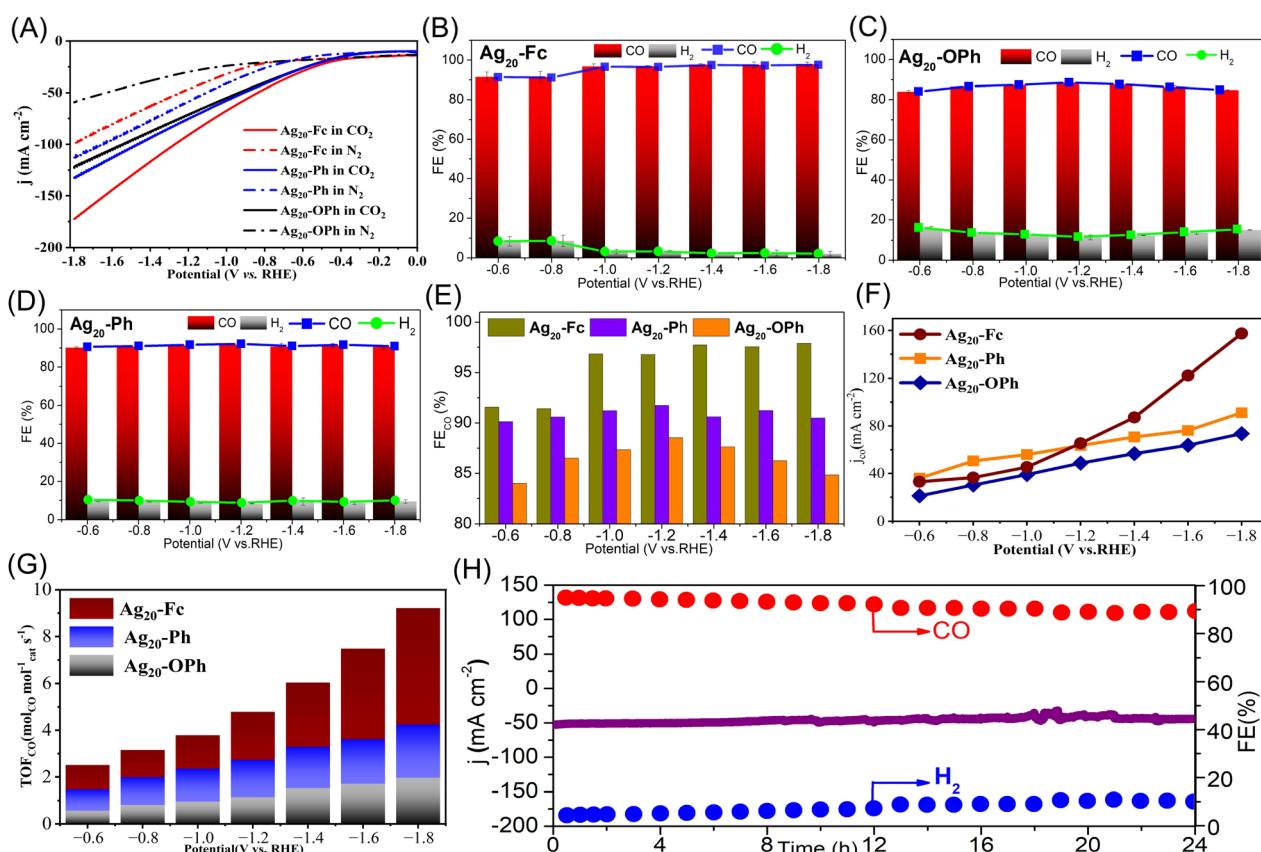


Fig. 5 (A) LSV of samples in N₂ or CO₂ saturated 1 M KOH solution; (B) FE values of Ag₂₀-Fc at different voltages; (C) FE values of Ag₂₀-OPh at different voltages; (D) FE values of Ag₂₀-Ph at different voltages; (E) comparison chart of FE_{CO} for three Ag₂₀ clusters; (F) comparison chart of CO partial current density (J_{CO}) for three Ag₂₀ clusters; (G) comparison chart of TOF values for three Ag₂₀ clusters; (H) i - t test and FE_{CO} values of Ag₂₀-Fc at −1.0 V vs. RHE in different time periods.



performance. To assess the catalyst's durability, we conducted a rigorous 24-hour chronoamperometric test at -1.0 V. Throughout the test, the current density remained above 50 mA cm^{-2} , and the FE_{CO} remained stable at over 90% (Fig. 5H). Additional characterizations, including powder X-ray diffraction (Fig. S41), ESI-MS (Fig. S42), X-ray photoelectron spectroscopy (Fig. S45), and transmission electron microscopy (Fig. S46), further confirmed that the catalyst retained its chemical composition and structural integrity throughout the electrolysis process.

To gain deeper insight into the origin of the enhanced catalytic activity imparted by ferrocene ligands, we carried out *in situ* electrochemical attenuated total reflection surface-enhanced infrared absorption spectroscopy (ATR-SEIRAS) measurements on $\text{Ag}_{20}\text{-Fc}$ (Fig. 6A) and $\text{Ag}_{20}\text{-Ph}$ (Fig. 6B) to monitor the evolution of key intermediates during the eCO₂RR process. Spectral changes were collected over a potential window from -0.6 to -1.8 V vs. RHE. A vibrational band at 1654 cm^{-1} , assigned to the O-H stretching mode of H₂O, indicates water activation and proton supply for PCET. Both catalysts display a characteristic absorption band at $\sim 1380\text{ cm}^{-1}$, attributable to the *COOH intermediate and corresponding to the C-OH stretching vibration.⁵⁶⁻⁵⁸ The progressive increase in intensity of this band at more negative potentials reflects the accumulation of *COOH species as the reaction proceeds. Remarkably, $\text{Ag}_{20}\text{-Fc}$ exhibits stronger and sharper *COOH signals than $\text{Ag}_{20}\text{-Ph}$ under identical conditions, demonstrating more effective stabilization of intermediates and a more reactive catalytic interface. In addition, both catalysts exhibit a distinct absorption band near 2100 cm^{-1} , assigned to adsorbed *CO, accompanied by a simultaneous decrease of the CO₂ band at 2355 cm^{-1} , confirming continuous CO₂ consumption. Importantly, the *CO band of $\text{Ag}_{20}\text{-Fc}$ is red-shifted by $\sim 20\text{ cm}^{-1}$ relative to that of $\text{Ag}_{20}\text{-Ph}$, indicating weaker *CO binding on the $\text{Ag}_{20}\text{-Fc}$ surface. Such weakened binding facilitates *CO desorption, thereby promoting CO release and enhancing turnover frequency. Collectively, these ATR-SEIRAS results demonstrate that $\text{Ag}_{20}\text{-Fc}$ features faster electron-transfer kinetics and more favorable intermediate

dynamics, consistent with its superior CO₂ reduction performance.

To further elucidate the role of the ferrocenyl group in regulating the reactivity of Ag_{20} NCs, we performed DFT calculations using $\text{Ag}_{20}\text{-Fc}$ and $\text{Ag}_{20}\text{-Ph}$ as model systems. The models were optimized based on their crystal structures, with the *tert*-butyl groups on TC4A replaced by H atoms to accelerate convergence. The optimized structures and corresponding Gibbs free energy diagrams for eCO₂RR and HER are shown in Fig. 7A. The calculations reveal that the formation of the *COOH intermediate is the rate-determining step of CO₂RR. The Gibbs free energy barrier for *COOH formation on $\text{Ag}_{20}\text{-Fc}$ is 1.60 eV , lower than the 1.88 eV calculated for $\text{Ag}_{20}\text{-Ph}$, highlighting the energy advantage of Ag sites in $\text{Ag}_{20}\text{-Fc}$ for CO₂-to-CO conversion (Fig. 7B). Since the two clusters share an identical metal framework and differ only in their alkynyl ligands, this discrepancy can be attributed to the electronic effect of the ferrocenyl group. The ferrocene moiety donates electrons to the Ag sites, rendering them more favorable for COOH formation. Moreover, the hydrogen adsorption free energy on $\text{Ag}_{20}\text{-Fc}$ is 1.75 eV , higher than the 1.51 eV of $\text{Ag}_{20}\text{-Ph}$, suggesting that $\text{Ag}_{20}\text{-Fc}$ is less favorable for H₂ evolution. Together, these findings demonstrate that ferrocenyl ligands not only stabilize critical *COOH intermediates but also suppress the competing HER, thereby enhancing the overall selectivity and activity of $\text{Ag}_{20}\text{-Fc}$ toward CO₂ reduction.

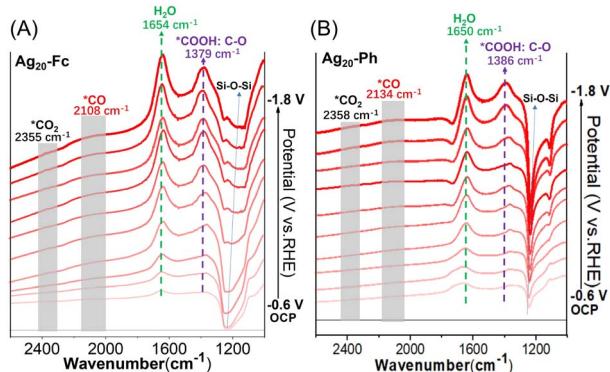


Fig. 6 ATR-FTIR test results of $\text{Ag}_{20}\text{-Fc}$ (A) and $\text{Ag}_{20}\text{-Ph}$ (B) in the $2600\text{--}1000\text{ cm}^{-1}$ range.

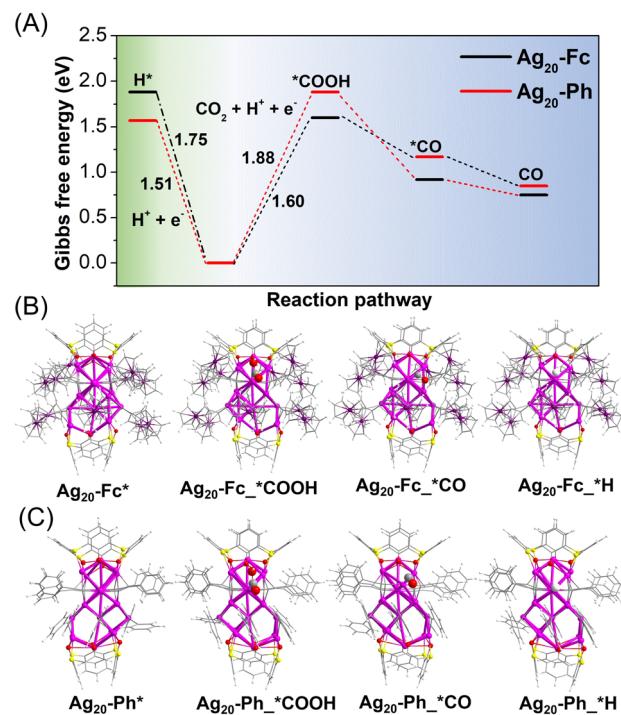


Fig. 7 (A) Free energy diagrams for the eCO₂RR and HER on $\text{Ag}_{20}\text{-Fc}$ and $\text{Ag}_{20}\text{-Ph}$; (B) schematic diagram of the eCO₂RR process on $\text{Ag}_{20}\text{-Fc}$; (C) schematic diagram of the eCO₂RR process on $\text{Ag}_{20}\text{-Ph}$.



Conclusions

In conclusion, this work provides atomic-level insights into the structure–activity relationships of silver nanocluster catalysts for CO₂ reduction. We demonstrate that organometallic ligand engineering—particularly the incorporation of ferrocenylacetylene ligands—offers an effective strategy for precisely tuning the catalytic properties of atomically defined nanoclusters. Anchoring twelve ferrocenylacetylene ligands onto the well-defined Ag₂₀–Fc cluster yields markedly enhanced performance, achieving a CO faradaic efficiency above 98% with stable operation exceeding 24 h. *In situ* infrared spectroscopy and DFT calculations reveal that the ferrocenyl groups lower the energy barrier for key intermediates, highlighting the critical role of ligand–metal interactions in optimizing active-site environments. These findings not only deepen the understanding of ligand effects in CO₂ electroreduction but also establish a general design principle for developing highly efficient, tunable, and scalable nanocluster-based catalysts.

Author contributions

C. L. supervised the project and conceived the idea. H. Y. Z carried out synthesis, characterization and catalytic experiment of clusters. L. Y. L undertook the calculations for this article. H. Y. Z and C. L. wrote the manuscript. All authors discussed the experimental results.

Conflicts of interest

There are no conflicts of interest to declare.

Data availability

CCDC 2464030–2464033, 2464035, 2464036 and 2475347 contain the supplementary crystallographic data for this paper.^{59a–g}

The data that support the findings of this study are available in the main text and the SI. Supplementary information: X-ray crystallographic file in CIF format, full experimental and computational details. See DOI: <https://doi.org/10.1039/d5sc06306j>.

Acknowledgements

This work was supported by the Open Research Project of the State Key Laboratory of Structural Chemistry (Grant No. 20250022) and the Innovation-Driven Research Program of Central South University (Grant No. 2023CXQD061).

Notes and references

- L. L. Zhuo, P. Chen, K. Zheng, X. W. Zhang, J. X. Wu, D. Y. Lin, S. Y. Liu, Z. S. Wang, J. Y. Liu, D. D. Zhou and J. P. Zhang, *Angew. Chem., Int. Ed.*, 2022, **61**, e202204967.
- Y. Song, W. Chen, C. Zhao, S. Li, W. Wei and Y. Sun, *Angew. Chem., Int. Ed.*, 2017, **56**, 10840–10844.

- L. Li, X. Li, Y. Sun and Y. Xie, *Chem. Soc. Rev.*, 2022, **51**, 1234–1252.
- J. Li, Y. Kuang, Y. Meng, X. Tian, W.-H. Hung, X. Zhang, A. Li, M. Xu, W. Zhou, C.-S. Ku, C.-Y. Chiang, G. Zhu, J. Guo, X. Sun and H. Dai, *J. Am. Chem. Soc.*, 2020, **142**, 7276–7282.
- P. Deng, H. Wang, R. Qi, J. Zhu, S. Chen, F. Yang, L. Zhou, K. Qi, H. Liu and B. Y. Xia, *ACS Catal.*, 2019, **10**, 743–750.
- H. Q. Fu, J. Liu, N. M. Bedford, Y. Wang, J. W. Sun, Y. Zou, M. Dong, J. Wright, H. Diao, P. Liu, H. G. Yang and H. Zhao, *Adv. Mater.*, 2022, **34**, 2202854.
- Z. Tao, C. L. Rooney, Y. Liang and H. Wang, *J. Am. Chem. Soc.*, 2021, **143**, 19630–19642.
- H. Seong, M. Choi, S. Park, H.-w. Kim, J. Kim, W. Kim, J. S. Yoo and D. Lee, *ACS Energy Lett.*, 2022, **7**, 4177–4184.
- G. Wang, J. Chen, Y. Ding, P. Cai, L. Yi, Y. Li, C. Tu, Y. Hou, Z. Wen and L. Dai, *Chem. Soc. Rev.*, 2021, **50**, 4993–5061.
- Q. Fan, P. Yan, F. Liu, Z. Xu, P. Liang, X. Cao, C. Ye, M. Liu, L. Zhao, S. Ren, H. Miao, X. Zhang, Z. Yang, X. Ding, J. Yang, C. Kong and Y. Wu, *Sci. Bull.*, 2024, **69**, 2881–2891.
- Y. Yang, J. Fu, Y. Ouyang, T. Tang, Y. Zhang, L.-R. Zheng, Q.-H. Zhang, X.-Z. Liu, J. Wang and J.-S. Hu, *Natl. Sci. Rev.*, 2023, **10**, nwac248.
- M. Zhang, M. Lu, M.-Y. Yang, J.-P. Liao, Y.-F. Liu, H.-J. Yan, J.-N. Chang, T.-Y. Yu, S.-L. Li and L. Y. Qian, *eScience*, 2023, **3**, 100116.
- Y. Y. Birdja, E. Pérez-Gallent, M. C. Figueiredo, A. J. Göttle, F. Calle-Vallejo and M. T. M. Koper, *Nat. Energy*, 2019, **4**, 732–745.
- X. Wang, M. H. Yu and X. L. Feng, *eScience*, 2023, **3**, 100141.
- D. Wang, J. J. Mao, C. C. Zhang, J. W. Zhang, J. S. Li, Y. Zhang and Y. F. Zhu, *eScience*, 2023, **3**, 100119.
- P. Li, J. Bi, J. Liu, Q. Zhu, C. Chen, X. Sun, J. Zhang and B. Han, *Nat. Commun.*, 2022, **13**, 1965.
- H. Li, T. Liu, P. Wei, L. Lin, D. Gao, G. Wang and X. Bao, *Angew. Chem., Int. Ed.*, 2021, **60**, 14329–14333.
- R.-X. Meng, C.-L. Zhao, P.-L. Luo, Y.-Q. Tian, Q. Tang, L.-K. Wang, J. Yan and C. Liu, *Chem. Sci.*, 2025, **16**, 6845–6852.
- 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.
- C. Du, J. P. Mills, A. G. Yohannes, W. Wei, L. Wang, S. Lu, J.-X. Lian, M. Wang, T. Guo, X. Wang, H. Zhou, C.-J. Sun, J. Z. Wen, B. Kendall, M. Couillard, H. Guo, Z. Tan, S. Siahrostami and Y. A. Wu, *Nat. Commun.*, 2023, **14**, 6142.
- Y. Gao, Q. Wu, X. Liang, Z. Wang, Z. Zheng, P. Wang, Y. Liu, Y. Dai, M. H. Whangbo and B. Huang, *Adv. Sci.*, 2020, **7**, 1902820.
- H. Seong, K. Chang, F. Sun, S. Lee, S. M. Han, Y. Kim, C. H. Choi, Q. Tang and D. Lee, *Adv. Sci.*, 2023, **11**, 2306089.
- L. J. Liu, Z. Y. Wang, Z. Y. Wang, R. Wang, S. Q. Zang and T. C. W. Mak, *Angew. Chem., Int. Ed.*, 2022, **61**, e202205626.
- G. Deng, H. Yun, M. S. Bootharaju, F. Sun, K. Lee, X. Liu, S. Yoo, Q. Tang, Y. J. Hwang and T. Hyeon, *J. Am. Chem. Soc.*, 2023, **145**, 27407–27414.
- Z.-H. Gao, K. Wei, T. Wu, J. Dong, D.-e. Jiang, S. Sun and L.-S. Wang, *J. Am. Chem. Soc.*, 2022, **144**, 5258–5262.



26 Y. Q. Tian, W. L. Mu, L. L. Wu, X. Y. Yi, J. Yan and C. Liu, *Chem. Sci.*, 2023, **14**, 10212–10218.

27 L. J. Li, W. L. Mu, Y. Q. Tian, W. D. Yu, L. Y. Li, J. Yan and C. Liu, *Chem. Sci.*, 2024, **15**, 7643–7650.

28 Z. Wang, L. Li, L. Feng, Z. Y. Gao, C. H. Tung, L. S. Zheng and D. Sun, *Angew. Chem., Int. Ed.*, 2022, **61**, e202200823.

29 K. Sheng, B. L. Han, Z. Wang, Z. Y. Gao, C. H. Tung and D. Sun, *Angew. Chem., Int. Ed.*, 2024, **64**, e202416065.

30 S. Biswas, A. K. Das, S. S. Manna, B. Pathak and S. Mandal, *Chem. Sci.*, 2022, **13**, 11394–11404.

31 L.-J. Li, Y.-T. Luo, Y.-Q. Tian, P. Wang, X.-Y. Yi, J. Yan, Y. Pei and C. Liu, *Inorg. Chem.*, 2023, **62**, 14377–14384.

32 W.-D. Si, H. Liang, S.-H. Ji, T. Kim, C. K. Zhang, Z. Wang, H.-F. Su, C.-H. Tung and D. Sun, *J. Am. Chem. Soc.*, 2025, **147**(36), 32458–32467.

33 H. Zhao, C. Zhang, B. Han, Z. Wang, Y. Liu, Q. Xue, C.-H. Tung and D. Sun, *Nat. Synth.*, 2024, **3**, 517–526.

34 Y. Chen, X. Zhou, X. Liu, Z. Tang, L. Wang and Q. Tang, *J. Am. Chem. Soc.*, 2025, **147**, 2699–2713.

35 X. Ma, F. Sun, L. Qin, Y. Liu, X. Kang, L. Wang, D.-e. Jiang, Q. Tang and Z. Tang, *Chem. Sci.*, 2022, **13**, 10149–10158.

36 G. Deng, J. Kim, M. S. Bootharaju, F. Sun, K. Lee, Q. Tang, Y. J. Hwang and T. Hyeon, *J. Am. Chem. Soc.*, 2022, **145**, 3401–3407.

37 S. Yoo, D. Kim, G. Deng, Y. Chen, K. Lee, S. Yoo, X. Liu, Q. Tang, Y. J. Hwang, T. Hyeon and M. S. Bootharaju, *J. Am. Chem. Soc.*, 2025, **147**, 12546–12554.

38 S.-F. Yuan, Z.-J. Guan and Q.-M. Wang, *J. Am. Chem. Soc.*, 2022, **144**, 11405–11412.

39 W.-L. Mu, L.-Y. Li, X.-Z. Cong, P.-K. Xia, X.-Y. Chen, Q.-Y. Liu, L.-K. Wang, J. Yan and C. Liu, *J. Am. Chem. Soc.*, 2024, **146**, 28131–28140.

40 X.-Y. Chen, L.-Y. Li, L.-C. Zhao, Q.-Y. Liu, D.-D. Ding, L.-K. Wang, H.-B. Mo, J. Yan and C. Liu, *Angew. Chem., Int. Ed.*, 2025, e202511232.

41 J. L. Hou, N. H. Huang, D. Acharya, Y. X. Liu, J. Y. Zhu, J. X. Teng, Z. Wang, K. Q. Qu, X. X. Zhang and D. Sun, *Chem. Sci.*, 2024, **15**, 2655–2664.

42 J. Y. Xu, L. Xiong, X. Cai, S. S. Tang, A. C. Tang, X. Liu, Y. Pei and Y. Zhu, *Chem. Sci.*, 2022, **13**, 2778–2782.

43 H.-N. Zhou, L.-Y. Li, Y.-X. Li, H.-B. Mo, J. Yan and C. Liu, *Chin. Chem. Let.*, 2025, **15**, 111269.

44 J.-H. Huang, H. Zhang, Z.-Y. Wang, J.-H. Hu, J. Li, J. Cai and S.-Q. Zang, *J. Am. Chem. Soc.*, 2025, **147**, 16593–16601.

45 V. K. Kulkarni, B. N. Khiarak, S. Takano, S. Malola, E. L. Albright, T. I. Levchenko, M. D. Aloisio, C.-T. Dinh, T. Tsukuda, H. Häkkinen and C. M. Crudden, *J. Am. Chem. Soc.*, 2022, **144**, 9000–9006.

46 T. Jia, Y.-X. Li, X.-H. Ma, M.-M. Zhang, X.-Y. Dong, J. Ai and S.-Q. Zang, *Nat. Commun.*, 2023, **14**, 6877.

47 Q. Yuan, S. Huang, H. Lin, G. Saranya, W. Hu, G. Li, X. Cai, X. Liu, M. Chen, W. Ding and Y. Zhu, *ACS Catal.*, 2023, **13**, 16188–16194.

48 J. Wang, X. Huang, S. Xi, H. Xu and X. Wang, *Angew. Chem., Int. Ed.*, 2020, **59**, 19162–19167.

49 M. G. Walawalkar, P. Pandey and R. Murugavel, *Angew. Chem., Int. Ed.*, 2021, **60**, 12632–12635.

50 G. Deng, H. Yun, Y. Chen, S. Yoo, K. Lee, J. Jang, X. Liu, C. W. Lee, Q. Tang, M. S. Bootharaju, Y. J. Hwang and T. Hyeon, *Angew. Chem., Int. Ed.*, 2024, **64**, e202418264.

51 Z. Xin, Y.-R. Wang, Y. Chen, W.-L. Li, L.-Z. Dong and Y.-Q. Lan, *Nano Energy*, 2020, **67**, 104233.

52 H. Zhang, S. Si, G. Zhai, Y. Li, Y. Liu, H. Cheng, Z. Wang, P. Wang, Z. Zheng, Y. Dai, T. X. Liu and B. Huang, *Appl. Catal., B*, 2023, **337**, 122909.

53 J. Liang, X. Gao, B. Guo, Y. Ding, J. Yan, Z. Guo, E. C. M. Tse and J. Liu, *Angew. Chem., Int. Ed.*, 2021, **60**, 12770–12774.

54 S. Yoo, S. Yoo, G. Deng, F. Sun, K. Lee, H. Jang, C. W. Lee, X. Liu, J. Jang, Q. Tang, Y. J. Hwang, T. Hyeon and M. S. Bootharaju, *Adv. Mater.*, 2023, **36**, 2313023.

55 J. Yan, B. K. Teo and N. Zheng, *Acc. Chem. Res.*, 2018, **51**, 3084–3093.

56 Z. J. Guan, R. L. He, S. F. Yuan, J. J. Li, F. Hu, C. Y. Liu and Q. M. Wang, *Angew. Chem., Int. Ed.*, 2022, **61**, e202116965.

57 J. Wang, F. Xu, Z. Y. Wang, S. Q. Zang and T. C. W. Mak, *Angew. Chem., Int. Ed.*, 2022, **61**, e202207492.

58 X.-K. Wan, J.-Q. Wang, Z.-A. Nan and Q.-M. Wang, *Sci. Adv.*, 2017, **3**, e1701823.

59 (a) CCDC 2464030: Experimental Crystal Structure Determination, 2025, DOI: [10.5517/ccdc.csd.cc2nq0v8](https://doi.org/10.5517/ccdc.csd.cc2nq0v8); (b) CCDC 2464031: Experimental Crystal Structure Determination, 2025, DOI: [10.5517/ccdc.csd.cc2nq0w9](https://doi.org/10.5517/ccdc.csd.cc2nq0w9); (c) CCDC 2464032: Experimental Crystal Structure Determination, 2025, DOI: [10.5517/ccdc.csd.cc2nq0xb](https://doi.org/10.5517/ccdc.csd.cc2nq0xb); (d) CCDC 2464033: Experimental Crystal Structure Determination, 2025, DOI: [10.5517/ccdc.csd.cc2nq0yc](https://doi.org/10.5517/ccdc.csd.cc2nq0yc); (e) CCDC 2464035: Experimental Crystal Structure Determination, 2025, DOI: [10.5517/ccdc.csd.cc2nq10g](https://doi.org/10.5517/ccdc.csd.cc2nq10g); (f) CCDC 2464036: Experimental Crystal Structure Determination, 2025, DOI: [10.5517/ccdc.csd.cc2nq11h](https://doi.org/10.5517/ccdc.csd.cc2nq11h); (g) CCDC 2475347: Experimental Crystal Structure Determination, 2025, DOI: [10.5517/ccdc.csd.cc2p2sxh](https://doi.org/10.5517/ccdc.csd.cc2p2sxh).

