

HIGHLIGHT

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Journey to the Holy Grail of a coordination saturated buckyball

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Exohedral metallofullerenes are increasingly gaining attention from both academia and industry due to their unique structural and electronic properties. C_{60} provides an incredible opportunity to bind up to 30 metals on the surface to realize an icosidodecahedral $C_{60}@M_{30}$ supramolecular complex, the Holy Grail of a coordination saturated buckyball. Recently, the Li and Zhan groups reported a rhombicuboctahedral $C_{60}@Cu_{24}$ core-shell structure, a giant leap on their journey toward the Holy Grail.

Since the discovery in 1985,¹ fullerene- C_{60} (buckyball) and its derivatives have always been a research hotspot because of their unique structures and physicochemical properties.^{2–17} One particular direction is to exploit the exohedral metallofullerenes,^{7–9,18,19} coordination complexes of transition metals (M) spreading over the surface of C_{60} binding to its C=C bonds in η^2 fashion, resulting in various C_{60} derivatives with intriguing photofunctional/electronic properties.⁴ As a spherical polyene system, the 30 C=C bonds of C_{60} provide an incredible opportunity to bind up to 30 metal atoms in a $\mu_{30}-(\eta^2)_{30}$ fashion and realize the $C_{60}@M_{30}$ core-shell structure, an icosidodecahedral supramolecular complex featuring 20 vertex-shared M_3 -trigons, the Holy Grail of a coordination saturated buckyball (Scheme 1).

Simple as it may seem, the highest nuclearity of the reported exohedral metallofullerenes to date is merely 6,^{8,9} including $C_{60}@M_6$ structures with six mononuclear clusters in η^2 fashion (octahedron geometry)²⁰ and two trinuclear clusters in $(\mu_3-\eta^2:\eta^2:\eta^2)$ fashion.²¹ Intuitively, metallofullerenes with nuclearity of more than 6 have been, until now, difficult to synthesize, most likely due to the steric crowding between bulky stabilizing ligands.

One of the key requisites to achieve a coordination saturated buckyball is adopting a vertex-shared M_3 -trigon coordination configuration. However, it seems like an impossible mission as the multiple auxiliary ligands surrounding the M_3 unit prevent other M_3 units from hovering over the neighbor hexagons and thus restrict the total number of M_3 units on the C_{60} surface, particularly for these open-shell transition metals with a coordination number no less than 4.

The studies of metallofullerenes can be dated back to the early 1990s, when several metal-coated fulleride clusters with high nuclearity such as $C_{60}@Li_{12}$,^{22,23} $C_{60}@Ba_{32}$, $C_{60}@Ca_{32}$,²⁴

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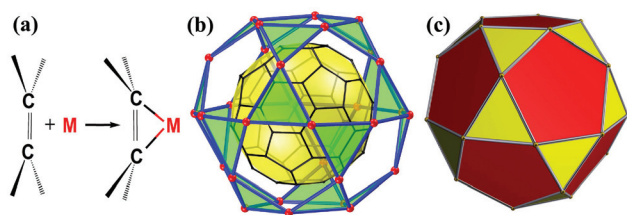
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Scheme 1 Formation of η²-fashion metal-olefin complex (a), the proposed icosidodecahedral C₆₀@M₃₀ structure in a μ₃₀-(η²)₃₀ coordination mode (b), and the icosidodecahedron polyhedron (c). For clarity, the coordination interactions between M and C=C are omitted in (b).

and others^{25,26} were speculated to exist under specific conditions. *Ab initio* molecular dynamics calculation revealed that C₆₀@Li₁₂ could be a stable cluster. However, their exact structures were not confirmed due to the lack of analytical techniques, preventing further investigation of their functions.

Recently, Li's group at Jinan University and Zhan's group at Shantou University jointly reported a rhombicuboctahedral C₆₀@Cu₂₄, a metallofullerene of unprecedented high nuclearity.²⁷ It is a giant leap toward complete coordination on the C₆₀ surface. Overall, the ingenious strategies in their endeavor toward high nuclearity include: (i) adopting closed-shell Cu(I) with a lower coordination number instead of open-shell metals and (ii) adopting anionic bridge ligands instead of terminal ligands. Both of these strategies were intended to minimize the steric crowd of the M₃ coordination sphere. As a continuous effort of the two research groups to explore metallofullerene complexes, four exohedral Cu(I)-C₆₀ (cuprofullerene) carboxylate complexes with nuclearities of 6, 12, and 24 were successfully synthesized by solvothermal reactions of fluorocarboxylic/bicarboxylic acid, Cu₂O, and C₆₀ in aromatic solvents. From a structure perspective, all of the cuprofullerene complexes embody the same coordination mode of [μ₃-η²:η²:η²]-C₆₀]-Cu₃-[(μ₂-κ¹:κ¹)-COO]₃ (Fig. 1a) with a Cu₃:C₆₀ ratio of 2:1, 4:1, and 8:1 (Fig. 1b–d). Particularly, the 24-nuclear cuprofullerene represents a rhombicuboctahedral C₆₀@Cu₂₄ core-shell structure with 8 Cu₃ units canopying on

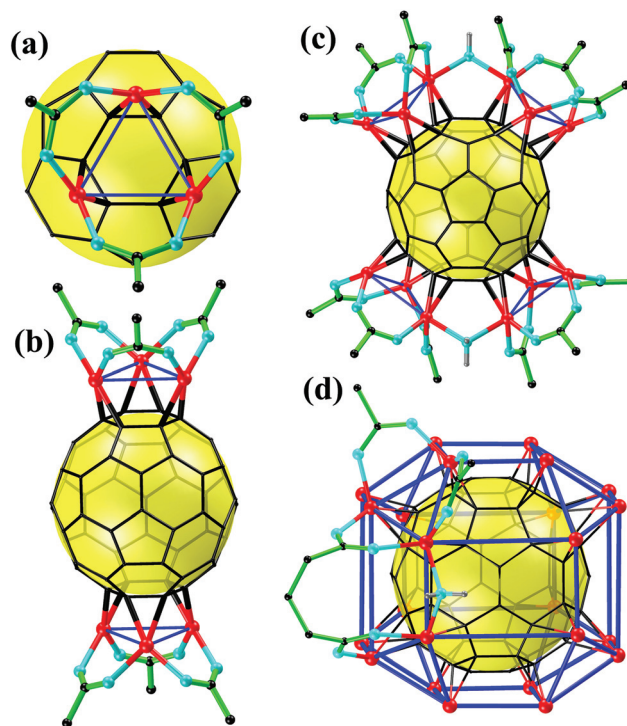


Fig. 1 The simplified structures of the synthesized cuprofullerenes. (a) Cu₃ unit, (b) C₆₀@Cu₆, (c) C₆₀@Cu₁₂ and (d) C₆₀@Cu₂₄. Color code: red, Cu; cyan, O; black, C; green, F; gray, H.

the 8 independent hexagons of C₆₀ (Fig. 1d), paving the road toward the completely coordinated C₆₀. For detailed structural analysis, please refer to their recently published paper.²⁷

As opposed to the reported exohedral M₃-metallofullerenes, in which the monodentate auxiliary ligands such as phosphine, CO, and isocyanide were frequently used,^{7–9} the synergistic associations of (μ₂-κ¹:κ¹)-carboxylate and (μ₃-η²:η²:η²)-hexagon could significantly enhance the stability of the Cu₃ units. Furthermore, the low coordination of Cu(I) and the outward orientation of carboxylates far away from the buckyball could endow the Cu₃ unit with much relieved steric crowd-



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Highlight

ing on the surface of C_{60} , which provides an opportunity to squeeze in more Cu_3 units on the adjacent hexagons to increase the overall nuclearity.

Besides adopting low coordination $Cu(I)$ and carboxylate as auxiliary ligands, the use of fluorocarboxylate as ligands might also play an essential role in the formation of cuprofullerene complexes of high nuclearity. Compared with the non-fluorinated carboxylate, the poorly coordinated fluorocarboxylate facilitates relatively strong association of the weak basic olefin C_{60} with $Cu(I)$, as reported in the $tris(\eta^2\text{-ethene})\text{-}Cu(I)$ cationic complexes.²⁸ As a matter of fact, using non-fluorinated *n*-butyl-carboxylate under similar conditions did not produce a complex of similar nuclearity. Inspired by the successful evolution of nuclearity from $C_{60}@Cu_6$ to $C_{60}@Cu_{12}$ through increasing the concentration of heptafluorobutyrate auxiliary ligands, the $C_{60}@Cu_{24}$ structure was eventually realized by using dicarboxylate, hexafluoroglutarate and glutarate, as bridging ligands, which is vital to further increase the local concentration of carboxylates around the surface of the buckyball. As a result, the bridging dicarboxylate provides extra bridging interactions beyond $\mu_2\text{-H}_2O$ associating eight Cu_3 units, further stabilizing the rhombicuboctahedral $C_{60}@Cu_{24}$ core-shell structure. It is worth pointing out that the authors were also able to obtain the extremely high-nuclear structure with non-fluorinated glutarate in 1-chloronaphthalene, in which the high solubility of C_{60} might have played an important role. It exemplifies the intricacy and complexity of the crystallization process, which leads us to believe that the final mission, the complete coordination of C_{60} , can be accomplished by the fine tuning of the reaction systems. In addition, by closely looking into the geometry of the obtained $C_{60}@Cu_{24}$ molecule, it appears there is enough space above the 6 vacant $C=C$ bonds to allow additional metal atoms and complete the proposed $C_{60}@Cu_{30}$ icosidodecahedron, provided the suitable auxiliary ligands are used. We look forward to the realization of the great Holy Grail by the authors as soon as possible.

Note that solvothermal conditions were utilized for the first time to prepare exohedral metallofullerene in this work. The high-boiling-point aromatic solvents make it possible to run the solvothermal reactions at rather high temperatures, and thus to overcome the energy barriers toward these high-nuclear cuprofullerenes.

The initial photophysical/photochemical properties were studied for the above-obtained Cu_3 -metallofullerenes. Their solid-state UV-Vis diffuse reflectance spectra exhibit absorption of the whole UV-visible area, indicating more efficient absorption of visible light than the pristine C_{60} due to the complexation of $Cu(I)$. Theoretical calculations confirmed that the complexation could reduce the symmetry and disturb the π -system of C_{60} , resulting in the symmetry-allowed excitation in the visible-light region. With the increase of nuclearity, the lowest absorptions of the four complexes show a hypsochromic shift, suggesting the potential influence of nuclearity on their electronic structures. Compared with the pristine C_{60} material, the cuprofullerene complexes show not only much higher efficient absorption of visible light, but also more controllable HOMO-LUMO gap, which implies an attractive prospect in utilizing solar energy.

As organocopper reagents, we could also expect these cuprofullerene complexes to function as novel catalysts in preparing organic fullerene derivatives,²⁹ opening a new door for organic fullerene chemistry.

Conclusions

In short, the Li and Zhan groups have successfully prepared a series of exohedral cuprofullerene complexes, featuring Cu_3 units canoping on the C_{60} surface in a $(\mu_3\text{-}\eta^2\text{:}\eta^2\text{:}\eta^2)$ fashion, by judiciously selecting fluorocarboxylate/dicarboxylate as auxiliary ligands and solvothermal reaction conditions. The ratio of $M_3:C_{60}$ has been expanded from 2:1 to 4:1 and 8:1, forming the unprecedented 12- and 24-nuclear cuprofullerenes. Particularly, the 24-nuclear complex, a rhombicuboctahedral $C_{60}@Cu_{24}$ core-shell structure, represents an exohedral metallofullerene of the most nuclearity, a giant leap toward the coordination saturated $C_{60}@M_{30}$. This work greatly enriches the structural diversity of exohedral metallofullerenes and is expected to bring advanced applications such as in the photoelectric conversion and catalytic synthesis of organic fullerene derivatives. We look forward to the realization of $C_{60}@M_{30}$ icosidodecahedron and its intriguing applications in the near future.

Conflicts of interest

There are no conflicts to declare.

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References

- 1 H. W. Kroto, J. R. Heath, S. C. O'Brein, R. F. Curl and R. E. Smalley, *C₆₀: Buckminsterfullerene*, *Nature*, 1985, **318**, 162–163.
- 2 D. M. Guldi and M. Prato, Excited-State Properties of *C₆₀* Fullerene Derivatives, *Acc. Chem. Res.*, 2000, **33**, 695–703.
- 3 H. Kang, W. Lee, J. Oh, T. Kim, C. Lee and B. J. Kim, From Fullerene–Polymer to All-Polymer Solar Cells: The Importance of Molecular Packing, Orientation, and Morphology Control, *Acc. Chem. Res.*, 2016, **49**, 2424–2434.
- 4 K. Lee, H. Song and J. T. Park, [60]Fullerene-Metal Cluster Complexes: Novel Bonding Modes and Electronic Communication, *Acc. Chem. Res.*, 2003, **36**, 78–86.
- 5 T. Wang and C. Wang, Endohedral Metallofullerenes Based on Spherical I_h-C₈₀ Cage: Molecular Structures and Paramagnetic Properties, *Acc. Chem. Res.*, 2014, **47**, 450–458.
- 6 J. Zhang, S. Stevenson and H. C. Dorn, Trimetallic Nitride Template Endohedral Metallofullerenes: Discovery, Structural Characterization, Reactivity, and Applications, *Acc. Chem. Res.*, 2013, **46**, 1548–1557.
- 7 A. L. Balch and M. M. Olmstead, Reactions of Transition Metal Complexes with Fullerenes (*C₆₀*, *C₇₀*, etc.) and Related Materials, *Chem. Rev.*, 1998, **98**, 2123–2165.
- 8 A. L. Balch and K. Winkler, Two-Component Polymeric Materials of Fullerenes and the Transition Metal Complexes: A Bridge between Metal–Organic Frameworks and Conducting Polymers, *Chem. Rev.*, 2016, **116**, 3812–3882.
- 9 M. A. Lebedeva, T. W. Chamberlain and A. N. Khlobystov, Harnessing the Synergistic and Complementary Properties of Fullerene and Transition-Metal Compounds for Nanomaterial Applications, *Chem. Rev.*, 2015, **115**, 11301–11351.
- 10 O. Ostroverkhova, Organic Optoelectronic Materials: Mechanisms and Applications, *Chem. Rev.*, 2016, **116**, 13279–13412.
- 11 S. S. Babu, H. Mohwald and T. Nakanishi, Recent progress in morphology control of supramolecular fullerene assemblies and its applications, *Chem. Soc. Rev.*, 2010, **39**, 4021–4035.
- 12 C. García-Simón, M. Costas and X. Ribas, Metallosupramolecular receptors for fullerene binding and release, *Chem. Soc. Rev.*, 2016, **45**, 40–62.
- 13 S.-Z. Zhan, J.-H. Li, G.-H. Zhang, M.-D. Li, S. Sun, J. Zheng, G.-H. Ning, M. Li, D.-B. Kuang, X.-D. Wang and D. Li, Coordination disk-type nano-Saturn complexes, *Chem. Commun.*, 2020, **56**, 3325–3328.
- 14 H. Cong, B. Yua, T. Akasak and X. Lu, Endohedral metallofullerenes: An unconventional core-shell coordination union, *Coord. Chem. Rev.*, 2013, **257**, 2880–2898.
- 15 A. Hirsch and M. Brettreich, *Fullerenes: Chemistry and Reactions*, Wiley-VCH, Weinheim, 2005.
- 16 Y. Zhang, M. Yao, M. Du, Z. Yao, Y. Wang, J. Dong, Z. Yang, B. Sundqvist, E. Kovats, S. Pekker and B. Liu, Negative Volume Compressibility in Sc₃N@C₈₀-Cubane Cocrystal with Charge Transfer, *J. Am. Chem. Soc.*, 2020, **142**, 7584–7590.
- 17 Y. Chai, X. Liu, B. Wu, L. Liu, Z. Wang, Y. Weng and C. Wang, In Situ Switching of Photoinduced Electron Transfer Direction by Regulating the Redox State in Fullerene-Based Dyads, *J. Am. Chem. Soc.*, 2020, **142**, 4411–4418.
- 18 P. J. Fagan, J. C. Calabrese and B. Malone, The Chemical Nature of Buckminsterfullerene (*C₆₀*) and the Characterization of a Platinum Derivative, *Science*, 1991, **252**, 1160–1161.
- 19 J. M. Hawkins, A. Meyer, T. A. Lewis, S. Loren and F. J. Hollander, Crystal Structure of Osmylated *C₆₀*: Confirmation of the Soccer Ball Framework, *Science*, 1991, **252**, 312–313.
- 20 P. J. Fagan, J. C. Calabrese and B. Malone, A multiply-substituted buckminsterfullerene (*C₆₀*) with an octahedral array of platinum atoms, *J. Am. Chem. Soc.*, 1991, **113**, 9408–9409.
- 21 B. K. Park, C. Y. Lee, J. Jung, J. H. Lim, Y.-K. Han, C. S. Hong and J. T. Park, [Os₃(CO)₆(PMe₃)₃](μ₃-η²:η²:η²-C₆₀)[Re₃(μ-H)₃(CO)₉]: A Fullerene[60] Coordinated to Two Different Trinuclear Clusters, *Angew. Chem., Int. Ed.*, 2007, **46**, 1436–1439.
- 22 Y. Chabre, D. Djurado, M. Armand, W. R. Romanow, N. Coustel, J. John, P. McCauley, J. E. Fischer and A. B. Smith, Electrochemical Intercalation of Lithium into Solid *C₆₀*, *J. Am. Chem. Soc.*, 1992, **114**, 764–766.
- 23 J. Kohanoff, W. Andreoni and M. Parrinello, A possible new highly stable fulleride cluster: Li₁₂C₆₀, *Chem. Phys. Lett.*, 1992, **198**, 472–477.
- 24 U. Zimmermann, N. Malinowski, U. Näher, S. Frank and T. P. Martin, Multilayer metal coverage of fullerene molecules, *Phys. Rev. Lett.*, 1994, **72**, 3542–3545.
- 25 F. Tast, N. Malinowski, S. Frank, M. Heinebrodt, I. M. L. Billas and T. P. Martin, Cage Destruction in Metal–Fullerene Clusters, *Phys. Rev. Lett.*, 1996, **77**, 3529–3532.
- 26 F. Tast, N. Malinowski, S. Frank, M. Heinebrodt, I. M. L. Billas and T. P. Martin, Transition metal coated fullerenes, *Z. Phys. D*, 1997, **40**, 351–354.
- 27 S.-Z. Zhan, G.-H. Zhang, J.-H. Li, J.-L. Liu, S.-H. Zhu, W. Lu, J. Zheng, S. W. Ng and D. Li, Exohedral Cuprofullerene: Sequentially Expanding Metal Olefin Up to a C₆₀@Cu₂₄ Rhombicuboctahedron, *J. Am. Chem. Soc.*, 2020, **142**, 5943–5947.
- 28 G. Santiso-Quinñones, A. Reisinger, J. Slattery and I. Krossing, Homoleptic Cu-phosphorus and Cu-ethene complexes, *Chem. Commun.*, 2007, **47**, 5046–5048.
- 29 Y. Matsuo and E. Nakamura, Selective Multiaddition of Organocopper Reagents to Fullerenes, *Chem. Rev.*, 2008, **108**, 3016–3028.