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Journey to the Holy Grail of a coordination saturated buckyball

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Received 7th May 2020, Accepted 3rd June 2020 DOI: 10.1039/d0qi00511h rsc.li/frontiers-inorganic 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} @M₃₀ supramolecular complex, the Holy Grail of a coordination saturated buckyball. Recently, the Li and Zhan groups reported a rhombicuboctahedral C_{60} @Cu₂₄ core-shell structure, a giant leap on their journey toward the Holy Grail.

Since the discovery in 1985,¹ fullerene-C₆₀ (C₆₀, 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 C₆₀ binding to its C=C bonds in η^2 fashion, resulting in various C₆₀ derivatives with intriguing photofunctional/electronic properties.⁴ As a spherical polyene system, the 30 C=C bonds of C₆₀ provide an incredible opportunity to bind up to 30 metal atoms in a μ_{30} -(η^2)₃₀ fashion and realize the C₆₀@M₃₀ core–shell structure, an icosidodecahedral supramolecular complex featuring 20 vertex-shared M₃-trigons, the Holy Grail of a coordination saturated buckyball (Scheme 1).

School of Chemistry and Chemical Engineering, Frontiers Science Center for Transformative Molecules and State Key Laboratory of Metal Matrix Composites, Shanghai Jiao Tong University, Shanghai 200240, China. E-mail: yongcui@sjtu.edu.cn Simple as it may seem, the highest nuclearity of the reported exohedral metallofullerenes to date is merely 6,^{8,9} including C_{60} @M₆ structures with six mononuclear clusters in η^2 fashion (octahedron geometry)²⁰ and two trinuclear clusters in (μ_3 – η^2 : η^2 : η^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} @Li₁₂,^{22,23} C_{60} @Ba₃₂, C_{60} @Ca₃₂,²⁴



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Scheme 1 Formation of η^2 -fashion metal-olefin complex (a), the proposed icosidodecahedral $C_{60} @M_{30}$ structure in a μ_{30} - $(\eta^2)_{30}$ 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 C_{60} @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(1)-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 $[\mu_3 - \eta^2: \eta^2: \eta^2: \eta^2] - C_{60} - Cu_3 - [(\mu_2 - \kappa^1: \kappa^1) - COO]_3$ (Fig. 1a) with a $Cu_3: C_{60}$ 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) Cu_3 unit, (b) $C_{60}@Cu_{60}@Cu_{12}$ and (d) $C_{60}@Cu_{24}$. Color code: red, Cu; cyan, O; black, C; green, F; gray, H.

the 8 independent hexagons of C_{60} (Fig. 1d), paving the road toward the completely coordinated C_{60} . 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 $(\mu_2 - \kappa^1 : \kappa^1)$ -carboxylate and $(\mu_3 - \eta^2 : \eta^2 : \eta^2)$ -hexagon could significantly enhance the stability of the Cu₃ units. Furthermore, the low coordination of Cu(1) and the outward orientation of carboxylates far away from the bucky-ball could endow the Cu₃ unit with much relieved steric crowd-



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Yan Liu

Yan Liu received her BS degree in applied chemistry in 2006 and PhD in chemistry in 2011 from Shanghai Jiao Tong University. She conducted her postdoctoral research at the University of North Carolina (2011–2013). She joined Shanghai Jiao Tong University in 2014, where she is now a professor of chemistry. Her research interest focuses on supramolecular chemistry and coordination chemistry. 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(1) 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(η^2 -ethene)-Cu(I) cationic complexes.²⁸ As a matter of fact, using non-fluorinated *n*-butylcarboxylate under similar conditions did not produce a complex of similar nuclearity. Inspired by the successful evolution of nuclearity from C60@Cu6 to C60@Cu12 through increasing the concentration of heptafluorobutyrate auxiliary ligands, the C₆₀@Cu₂₄ 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 μ_2 -H₂O associating eight Cu₃ units, further stabilizing the rhombicuboctahedral C60@Cu24 coreshell 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 C₆₀ 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 C₆₀, can be accomplished by the fine tuning of the reaction systems. In addition, by closely looking into the geometry of the obtained C60@Cu24 molecule, it appears there is enough space above the 6 vacant C=C bonds to allow additional metal atoms and complete the proposed C60@Cu30 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.



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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 highnuclear cuprofullerenes.

The initial photophysical/photochemical properties were studied for the above-obtained Cu₃-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 C₆₀ due to the complexation of Cu(I). Theoretical calculations confirmed that the complexation could reduce the symmetry and disturb the π -system of C₆₀, 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 C₆₀ 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 Cu₃ units canopying on the C₆₀ surface in a $(\mu_3 - \eta^2: \eta^2: \eta^2)$ 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 C60@Cu24 core-shell structure, represents an exohedral metallofullerene of the most nuclearity, a giant leap toward the coordination saturated C60@M30. 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 C60@M30 icosidodecahedron and its intriguing applications in the near future.

Conflicts of interest

There are no conflicts to declare.

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