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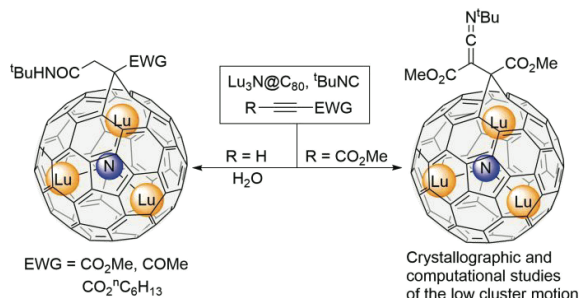
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Multicomponent Reactions Among Alkyl Isocyanides, *sp* reactants, and *sp*² Carbon Cages

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Abstract We explored the reactivity and substrate scope of the reactions among an alkyl isocyanide, an *sp*-hybridized reactant (i.e. alkyne or allene), and a carbon cage, as a new approach to functionalize fullerenes and metallofullerenes. This account summarizes the key findings in our recent published work, and some original data for the reaction involving an isocyanide, allenes, and metallofullerene Lu₃N@C₈₀.

Key words isocyanide, cluster motion, endohedral, fullerenes, multicomponent reaction

1. Introduction

Endohedral metallofullerenes (EMFs) have many intriguing properties due to their unique structures with metal atoms or clusters encapsulated inside a fullerene carbon cage.¹ The successful encapsulation of rare-earth¹ and actinide metal ions² provide an isolated and protected environment for the metal species, which lead to broad range of applications, including single molecular magnets,³ spin-quantum computing,⁴ artificial photosynthesis,⁵ dynamic nuclear polarization,⁶ magnetic resonance imaging (MRI) contrast agents,⁷ and therapeutic agents.⁸

A subgroup of EMFs, the nitride clusterfullerenes (NCFs), or the so-called trimetallic nitride template (TNT) EMFs,⁹ are significantly stabilized by the six electrons transferred from the endohedral cluster M₃N to the cage.¹⁰ The species with highest symmetry and most production yield in the NCF family, M₃N@I_h-C₈₀ (M = Sc, Y, lanthanides, "@" denotes encapsulation, I_h refers to the point group symmetry of the cage and is written in italic by

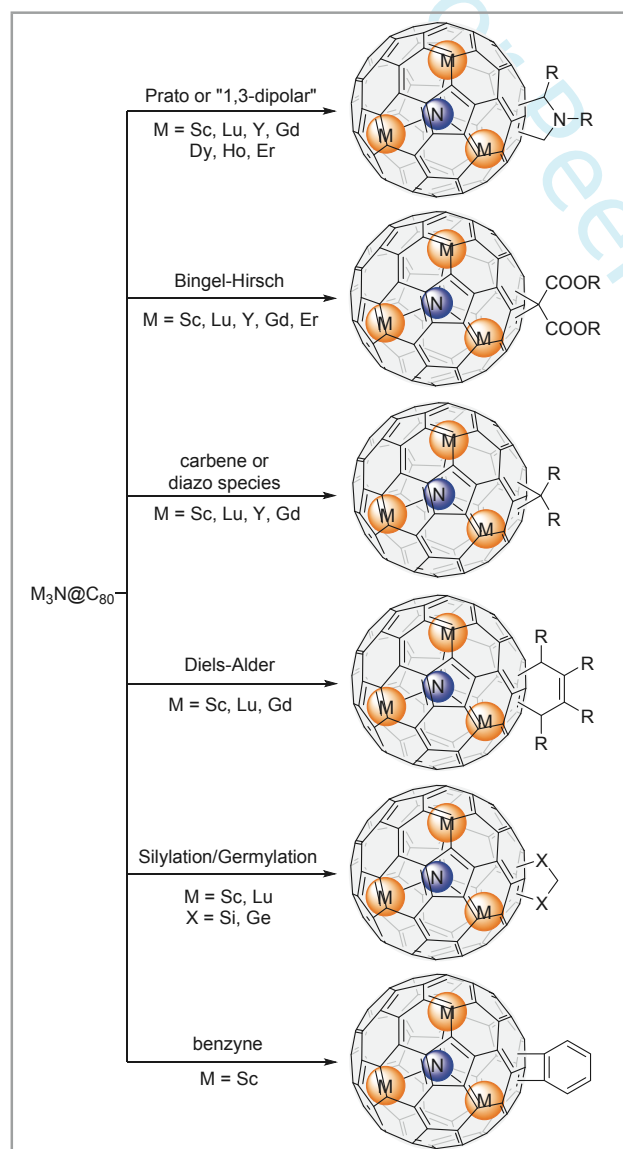
convention),¹¹ are particularly stable which poses challenges on their chemical functionalization.

The exohedral functionalization of EMFs generally increases the solubility and allows for structural building for desired materials functions.^{1a} The chemical reactivity of EMFs is very different from empty cage fullerenes due to the electron transfer from the encapsulated atoms to the carbon cages, which makes them generally more inert as electron acceptors.¹² Only a small percentage of reactions reported for empty fullerenes^{1b} has been successfully applied to EMFs. Among these less reactive EMFs, NCFs sharing a closed shell structure with up to six electrons transferred from the metal cluster towards the fullerene cage, show a consequential decrease of reactivity that makes their chemical modification challenging.^{10, 13} The reported NCF M₃N@C₈₀ reactions (Scheme 1) mainly include Prato reactions,¹⁴ Bingel–Hirsch reactions,¹⁵ carbene¹⁶ or diazo additions,¹⁷ Diels–Alder reactions,¹⁸ silylation and germylation,¹⁹ benzyne additions,²⁰ radical additions,²¹ reactions with azides,²² reactions with special 1,3-dipoles,²³ coordination,²⁴ dimerization²⁵ and EMF anion-induced reactions.²⁶ Overall, chemical methods to modify M₃N@I_h-C₈₀, especially those are not adopted from a well-established C₆₀ reaction, are still in high demand.

2. Isocyanide-induced fullerene/EMF reactions with substituted alkynes

As cycloadditions dominate the successful reactions on NCFs, one strategy to develop new reactions is to find reactive species that can react with alkenes, similar to the diene in a Diels–Alder reaction or the 1,3-dipole in a Prato reaction. In our recent work,^{27, 28} we had our eye on *sp*-hybridized carbon reactants linked to an electron-withdrawing group (EWG), which react with alkyl isocyanide to generate reactive dipolar species, to be captured by a third, alkenyl reactant. These multicomponent reactions have been widely used to construct cyclic structures in organic synthesis using alkynes²⁹ and allenes.³⁰ When an alkyl isocyanide reacts with an alkyne, they are expected to form a

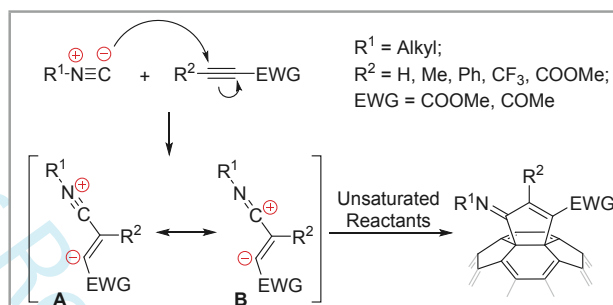
reactive species, represented by two resonance forms A and B, shown in Scheme 2. When they react with fullerenes or EMFs, the most straightforward prediction for the cycloaddition product should be a [3+2] addition from **A** or **B** (Scheme 2). However, the sole example of such reactions on fullerene species, reported in 2005, among *t*-butyl isocyanide (^tBuNC), a special alkyne dimethyl acetylenedicarboxylate (DMAD), and empty cage C₆₀, was reported to give two fullerene derivatives: [3+2] cycloadduct, and a [2+2] cycloadduct,³¹ with the latter very surprising to our understanding. We carefully examined the report, and found that the structural elucidation of the products lacked crystallographic proof, while the spectroscopic characterization of the [2+2] product was rather ambiguous. Therefore, we explored the utility of the isocyanide-induced reactions with various *sp*-hybridized substrates, on fullerene C₆₀²⁸ and EMF Lu₃N@I_h-C₈₀²⁷ concurrently. In the notably stable family of M₃N@I_h-C₈₀, Lu and Sc are the more inert members,³² which means if the reactions on Lu₃N@C₈₀ were successful, they are likely to work on other EMFs as well.



Scheme 1 Typical cycloaddition reactions of TNT-EMFs. In the scheme,

all products are drawn in a general form without specifying the bonds at the reaction sites (i.e., [5,6] vs [6,6] bond, open vs close cage).

Unexpectedly, from all the C₆₀ and Lu₃N@C₈₀ reactions with alkyl isocyanides and alkynes, the major product was neither [2+2] nor [3+2] products. Instead, they are resulted from a cyclopropanation process, as both were confirmed by crystallography. With the aid of density functional theory (DFT) calculations, we found the reaction mechanism on Lu₃N@C₈₀ is a stepwise attack, similar to a Bingel-Hirsch reaction,^{15a} and we conjecture the mechanism for the C₆₀ reactions were the same. There are key differences in the EMF and empty fullerene derivatives though. First, EMF reactions gave almost exclusively cyclopropyl products, while C₆₀ reactions gave cyclopropyl and [3+2] products. Second, the Lu₃N@C₈₀ cyclopropyl derivatives rearranged into open-cage metallofulleroids, whereas the C₆₀ cyclopropyl derivatives remained as close-cage methanofullerenes. For many of the cyclopropyl products, spontaneous hydration occurred in quantitative yields, but the DMAD reactions yielded stable ketenimine products without hydration.

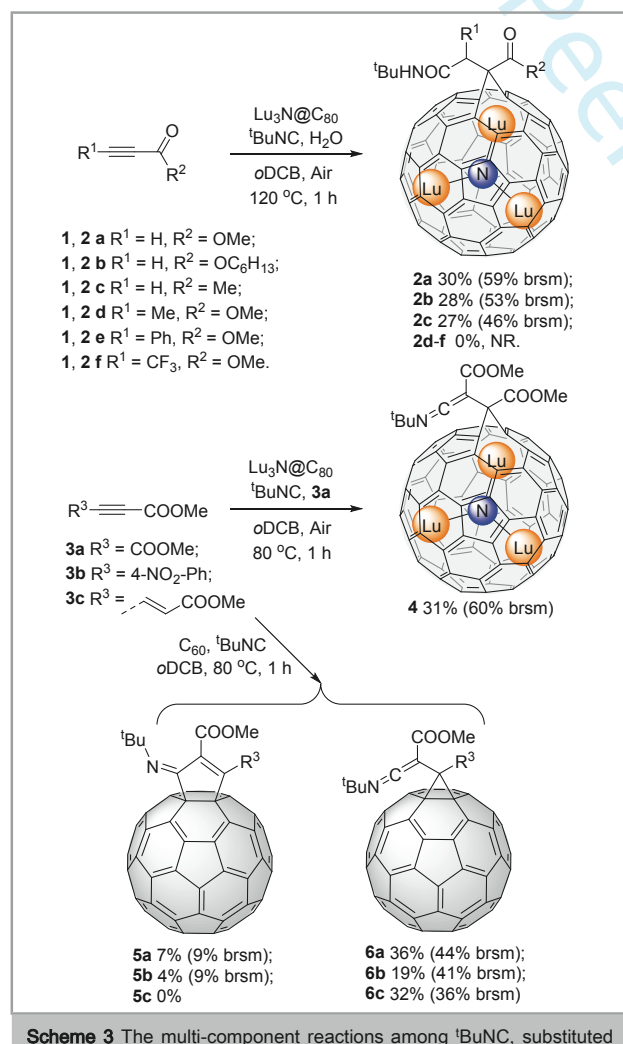


Scheme 2 Reactive species formed from an alkyl isocyanide and alkynes linking an electron-withdrawing group

There are also important differences in the reactivity and substrate scope. We started with the multicomponent reaction among Lu₃N@C₈₀, ^tBuNC and an EWG-bearing terminal alkyne, with the EWG being a carbonyl or an ester group (**1a-c** in Scheme 3).²⁷ All three generated a dominate product in decent yields. Then, keeping an ester EWG, we changed the terminal alkynes to internal alkynes, none of the **1d-f** worked, and the only exception was the symmetric internal alkyne DMAD. For C₆₀, however, terminal or internal alkynes **1a-f** all failed, and only DMAD yielded two products, as previously reported,³¹ except the once-considered [2+2] products were actually methanofullerenes (Scheme 3). On the other hand, when we further explored the substrate scope for C₆₀, we found that two other internal alkynes also reacted (Scheme 3), with either an allylic or a 4-nitrophenyl group. Our results suggested that for C₆₀ reactions, electron-withdrawing resonance effects on the triple bond were critical.

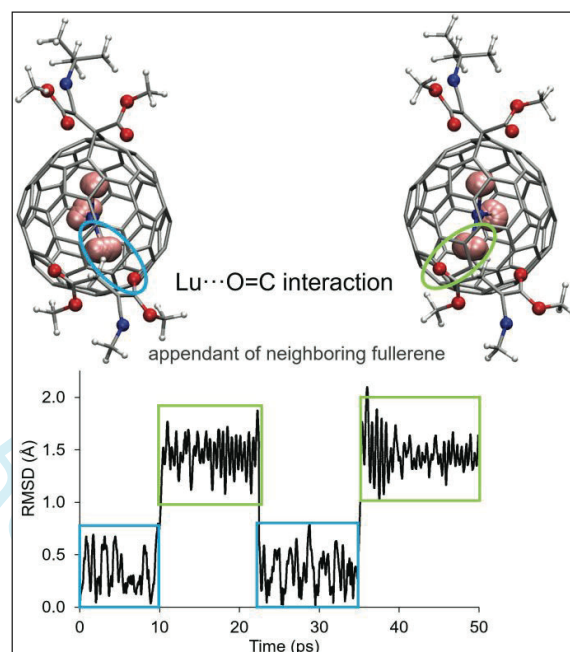
An intriguing feature of product **4** is that the endohedral Lu₃N cluster was fully ordered in crystal studies at 120 K. Monitoring the cluster in the crystal of **4** at different temperatures (120, 250, 298 K) indicate that the cluster motion started at higher temperature compared to most M₃N@C₈₀ monoderivatives and may not have fully free cluster motion even at room temperature. This is very different from **2a** and **2c**, which have highly disordered clusters at 120 K, with very similar structures. We had

to consider the possibility that the differences in the size and shape of the organic appendants, caused by the extra ester group in **4** vs the hydration step in **2a**, **2c**, led to the difference. Indeed, careful examination of the crystal profiles revealed that the molecules of **4** pack tighter than **2a** and **2c** in solid state, with shorter distance between the EMF cage and the carbonyl oxygen atoms on the appendant from an adjacent molecule. The interaction was studied by DFT calculations using the PBE functional. The rotational energy barrier of the Lu_3N cluster around the Lu1-N axis were similar for **2a** and **4** (2.5 kcal/mol), when only single molecule was considered. However, when the appendant of the neighboring molecule, which is present in the crystal packing of **4** but absent in **2a** and **2c**, is considered in the computation, the barrier for the rotation significantly increased to 6–7 kcal/mol. Car-Parrinello molecular dynamics (CPMD) simulations confirms that the cluster motion in **4** is controlled externally by the appendant, especially the two carbonyl O atoms of the dicarboxylate, of another neighboring molecule. The DFT finding enabled the understanding of the origin of the interaction that dictated the lack of cluster rotation in **4**, which was further corroborated with CPMD simulations showing that one Lu atom is actually interacting alternatively back and forth with the two carbonyl oxygen atoms of the dicarboxylate (Figure 1).



alkynes, and $\text{Lu}_3\text{N@C}_{80}$ or C_{60} . brsm = based on recovered starting material; NR = No reaction.

Temperature-dependent cluster rotation modulated by non-covalent interactions have been demonstrated for unfunctionalized NCFs theoretically and experimentally.³³ In functionalized NCFs, fully ordered clusters were mostly achieved via direct and strong interactions between the functional group and the cage (e.g. multi-additions, or formal charge on the ligand and cage, etc.)^{16b, 21c, 24, 34} Our work demonstrated that weak intermolecular interactions between the organic ligands and the NCF cage can also restrict the cluster motion in the solid state of synthetically straightforward monoadducts, which provides a new direction of materials design for magnetic and quantum applications.



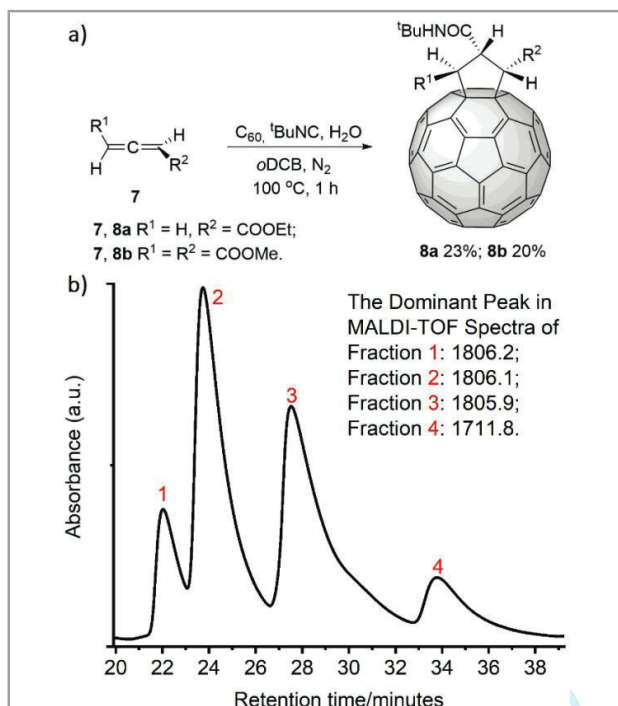


Figure 2 a) Four-component reactions of C_{60} , $tBuNC$, **7** and H_2O . b) HPLC spectrum (2 mL/minute, toluene, 5PYE) of the products isolated via silica gel column from the multicomponent reaction of $Lu_3N@C_{80}$, $tBuNC$ and **7a**.

3. Isocyanide-induced fullerene/EMF reactions with substituted allenes

Allenes represent another form of *sp* carbon atoms, which are also used with alkyl isocyanides to create cyclic structure in organic synthesis via multi-component reactions (Figure 2a).³⁰ Replacing the triple bond with cumulated double bonds, ethyl buta-2, 3-dienoate **7a** and dimethyl 2, 3-pentadienedioate **7b**, the allenolate counterpart of **1a** and DMAD, were attempted in the multicomponent reactions, which yielded **8a** and **8b** from four-component reactions among $tBuNC$, allenolate, C_{60} and one molecule of water.²⁸

Not reported in our papers,^{27,28} similar reactions were performed on $Lu_3N@C_{80}$. The reaction involving **7a**, $tBuNC$ and $Lu_3N@C_{80}$ gives only one product spot on TLC (although the combined conversion rate is rather low), which was isolated via flash chromatography and then studied with HPLC on 5PYE column (Figure 2b). There are four major peaks on the HPLC spectrum, which have been isolated from each other and tested by MALDI-TOF MS respectively. Peaks 1-3 share the similar MS value 1806, equal to the sum of one molecule of $Lu_3N@C_{80}$, one molecule of $tBuNC$ and two molecules of **7a**, while peak 4 gives clear molecular ions 1712 corresponding to a mass of three reactants plus one molecule of water. The existence of the major peaks 1-3 on HPLC spectrum reveals that the addition pattern of the reaction is clearly different from that of the C_{60} . Due to the poor selectivity and low conversion of $Lu_3N@C_{80}$ starting material, which did not improve via varying reaction conditions, we chose to not scale up this reaction. It was hypothesized that the poor selectivity might be caused by the asymmetry of **7a**, so symmetric substrate **7b** was attempted in such reaction, but no reaction

occurred despite of our optimization effort. We include this result not only to report this preliminary finding, but also to alert readers (especially young researchers) about a common situation in the field of EMF functionalization: a lot of times reactions occur, but due to the limitations in conversion (yield), selectivity, solubility, or sometimes, the challenges in crystallization, these results may take a long time to publish, or do not get published.

Table 1 Different reactivities of $Lu_3N@C_{80}$ and C_{60} ^a

Substrate	$Lu_3N@C_{80}$	C_{60}
1a-c	[6,6]-Open metallofulleroids 2a-c	No isolable products
3a	[6,6]-Open ketenimine metallofulleroid 4	[6,6]-Closed [3+2] cycloadduct 5a and ketenimine methanofullerene 6a
3b	No reaction	[6,6]-Closed [3+2] cycloadduct 5b and ketenimine methanofullerene 6b
3c	[6,6]-Open ketenimine metallofulleroid	[6,6]-Closed ketenimine methanofullerene 6c ^a
7a	Low conversion and poor selectivity	[6,6]-Closed cyclopentano fullerene 8a
7b	No reaction	[6,6]-Closed cyclopentano fullerene 8b

^a The reaction involving **3c** and $Lu_3N@C_{80}$ gives similar product as **6c** based on primary characterization data including MALDI-TOF MS and NMR spectra without single crystal data.

In conclusion, isocyanide-induced multicomponent reactions involving *sp*-hybridized alkynes and allenes have been investigated on $Lu_3N@C_{80}$ and C_{60} . Endohedral fullerene- $Lu_3N@C_{80}$ and empty fullerene- C_{60} show different reactivities, as summarized in Table 1. Notably, metallofulleroid **4** showed restricted cluster motion caused by the close interaction with the exohedral organic appendant of a neighbor molecule. These multi-component annulation reactions can be explored with other carbon cages, such as C_{70} and the other endohedral fullerenes.

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