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Size Effect of Encaged Clusters on the Exohedral Chemistry of Endohedral Fullerenes: A Case Study on the Pyrrolidino Reaction of $Sc_xGd_{3-x}N@C_{80}$ ($x = 0$–3)

Ning Chen,[†,‡] Er-Yun Zhang,[†,‡] Kai Tan,[§] Chun-Ru Wang,*[,†] and Xin Lu*[,§]

Beijing National Laboratory for Molecular Sciences (BNLMS), Institute of Chemistry, Chinese Academy of Sciences, Beijing 100080, China, Graduate University of the Chinese Academy of Sciences, Beijing 100080, China, and State Key Laboratory of Physical Chemistry of Solid Surfaces and Center for Theoretical Chemistry, College of Chemistry and Chemical Engineering, Xiamen University, Xiamen, 361005, China

crwang@iccas.ac.cn; xinlu@xmu.edu.cn

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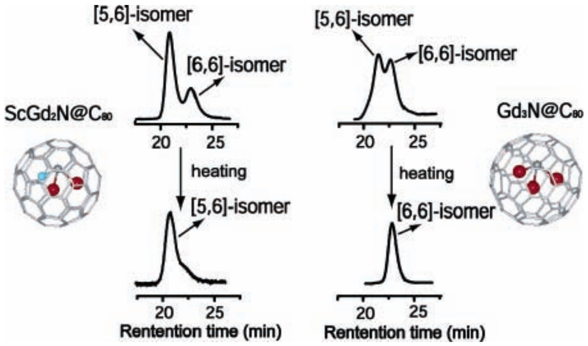
ABSTRACT



We report a combined experimental and theoretical investigation on the regiochemistry of a series of TNT endohedral fullerenes $Sc_xGd_{3-x}N@C_{80}$ ($x = 0$–3) in 1,3-dipolar cycloadditions, which demonstrates that the regioselectivity of the TNT-based endohedral fullerenes $Sc_xGd_{3-x}N@C_{80}$ ($x = 0$–3) in the exohedral cycloadditions depends remarkably on the size of the encaged cluster.

Since the discovery of endohedral metallofullerene (EMF) $La@C_{60}$ in 1985,[1] a large number of EMFs have been synthesized and characterized over the past two decades.[2] However, little has been known about the exohedral chemistry of EMFs until very recently. The C_{80}-I_h-based EMFs, $La_2@C_{80}$ and $M_3N@C_{80}$ (M = Sc, Y), were recently found to be subject to exohedral [4+2] and 1,3-dipolar cycloadditions.[3,4] It was observed that the 1,3-dipolar cycloaddition of azomethine ylide to $M_3N@C_{80}$ (M = Sc, Y) can occur at the [5,6]- and [6,6]-ring fusions of the C_{80}-I_h cage, but the kinetically favored [6,6]-adduct can be quickly and completely transformed into the thermodynamically more stable [5,6]-adduct in the $Sc_3N@C_{80}$ case,[4b] whereas such transformation is incomplete in the $Y_3N@C_{80}$ case.[4a,5] This implies the size of the endohedral cluster subtly affects the regiochemistry of $Sc_3N@C_{80}$ and $Y_3N@C_{80}$, since these trimetallic

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[†] Institute of Chemistry, Chinese Academy of Sciences.
[‡] Graduate University of the Chinese Academy of Sciences.
[§] Xiamen University.

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nitride template (TNT) endohedral fullerenes share the same I_h-C_{80} cage with similar electronic structures $(M_3N)^{6+}@C_{80}{}^{6-}$. Note that in addition to $Sc_3N@C_{80}$[6a] and $Y_3N@C_{80}$, a number of TNT endohedral fullerenes $M_3N@C_{80}$ (M = lanthnide such as Gd, Dy, etc.)[7] also have been synthesized and all of them have the similar valence state $(M_3N)^{6+}@C_{80}{}^{6-}$ but different sizes of the endohedral M_3N cluster. Among them, the $Gd_3N@C_{80}$ has the largest encaged cluster. If the regiochemistry of the TNT endohedral fullerenes depends largely on the size of the endohedral cluster, we wonder if the $Gd_3N@C_{80}$ would show thoroughly different regiochemistry from that of $Sc_3N@C_{80}$ and $Y_3N@C_{80}$ in the 1,3-dipolar cycloaddition. Herein we report a combined experimental and theoretical investigation on the regiochemistry of a series of TNT endohedral fullerenes $Sc_xGd_{3-x}N@C_{80}$ ($x = 0-3$) in 1,3-dipolar cycloadditions, which demonstrates that the [6,6]-pyrrolidino-adducts of $Gd_3N@C_{80}$ is the major product with minor [5,6]-pyrrolidino-adducts, a regioselectivity that is drastically different from that of $Y_3N@C_{80}$[4a] and $Sc_xGd_{3-x}N@C_{80}$ ($x = 1-3$).

The endohedral fullerenes $Sc_xGd_{3-x}N@C_{80}$ ($x = 0-3$) were prepared and characterized following a similar process as previously reported.[6] Isomerically pure samples of 10 mg of $Sc_3N@C_{80}$, 5 mg of $Sc_2GdN@C_{80}$, 5 mg of $ScGd_2N@C_{80}$, and 1 mg of $Gd_3N@C_{80}$ were isolated and dried in a vacuum. Next, ca. 0.5 mg of each sample was taken to dissolve in *o*-dichlorobenzene, and the solution was heated to 115 °C; afterward ^{13}C-enriched formaldehyde and an excess of *N*-ethylglycine were added to react with the endohedral fullerenes under this temperature. After 15 min, the samples were cooled and HPLC with a Buckyprep-M column was applied to isolate the reacting products. The resulting HPLC profiles for the four samples are shown in Figure 1. Each fraction of the HPLC profiles was collected and analyzed by Matrix Assisted Laser Desorption/Ionization Mass Spectrometry (MALDI-MS) to determine the composition. The fractions with retention time at 19.6−23.9 min were assigned as the pyrrolidinofullerene monoadducts (Figure S1), and other fractions were *o*-dichlorobenzene, the unreacted $Sc_xGd_{3-x}N@C_{80}$($x = 0-3$), and pyrrolidinofullerene bisadducts, respectively (Figure 1).

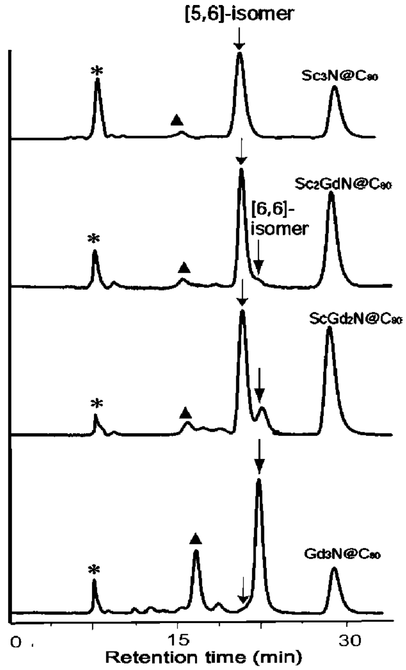

Figure 1. HPLC (Buckyprep-M, toluene eluent at 12 mL/min) profile of products of 1,3-dipolar cycloaddition of *N*-ethylazomethine ylide, in which pyrrolidinofullerenes $[C_4H_9N]$-$Sc_xGd_{3-x}N@C_{80}$ ($x = 0-3$) are the main products: (*) *o*-dichlorobenzene peak and (▲) bisadducts of $Sc_xGd_{3-x}N@C_{80}$ ($x = 0-3$) fullerenes.

The cycloaddition reactions of *N*-ethylazomethine ylide with $Sc_3N@C_{80}$ and $Y_3N@C_{80}$ under similar conditions have been studied previously.[4b] It was revealed that the retention times of the pyrrolidinofullerenes on Buckyprep-M column depend exclusively on the [5,6]- or [6,6]-regioisomers, regardless of the different encaged M_3N clusters. This was ascribed to the fact that all the $M_3N@C_{80}$-I_h analogues have the same C_{80}-I_h cage and similar electronic structure.[4a] Accordingly, the retention time can be used as a convenient tool to assign the regioisomers of the $M_3N@C_{80}$ analogues concerned herein.

As shown in Figure 1, a single peak (retention time 20.1 min) of the $Sc_3N@C_{80}$ monoadducts in the HPLC profile should represent the well-characterized [5,6]-$[C_4H_9N]$-$Sc_3N@C_{80}$.[4b] Beginning with $Sc_2GdN@C_{80}$, a second peak appears after the [5,6]-regioisomer peak, which is shown as a peak tail in the HPLC profile of $Sc_2GdN@C_{80}$ derivatives,[8] a minor peak in the HPLC profile of $ScGd_2N@C_{80}$ derivatives, and the major peak in the HPLC profile of $Gd_3N@C_{80}$ derivatives.[9] MALDI-MS study reveals that the second peak has the same chemical composition as the first [5,6]-

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pyrrolidino-adduct peak. It was assigned as the [6,6]-pyrrolidino-adduct of $Gd_3N@C_{80}$, because its retention time (∼22.7 min) is identical with the retention time (22.7 min) of the [6,6]-pyrrolidino-$Y_3N@C_{80}$ under the same HPLC condition. From Figure 1, it is clear that the [6,6]-product becomes more and more favored with the increasing TNT size from Sc_3N to Gd_3N, and the [6,6]-product finally became the major regioisomer in the Gd_3N case.

To further explore the relative thermostability of the [6,6]- and [5,6]-regioisomers, we then performed a thermal treatment of the reacting products at 180 °C for 1 h in combination with HPLC analyses. The results showed the following: (a) the major [5,6]-regioisomer of pyrrolidino-$Sc_3N@C_{80}$ is unchanged after thermalization as previously reported,[4b] (b) the minor [6,6]-regioisomer of the $Sc_2GdN@C_{80}$ derivative is completely isomerized to [5,6]-regioisomer; (c) the minor [6,6]-regioisomer of the $ScGd_2N@C_{80}$ derivative is partially isomerized to the [5,6]-regioisomer (Figure 2a,b), suggesting that in this case the energy difference between [5,6]- and [6,6]-isomers is very small; and (d) the major [6,6]-pyrrodino-$Gd_3N@C_{80}$ is unchanged, whereas the minor [5,6]-adducts (enriched sample, Figure 2c,d) is isomerized to [6,6]-adducts, indicating that [6,6]-adducts are both kinetically and thermdynamically favored in this case.

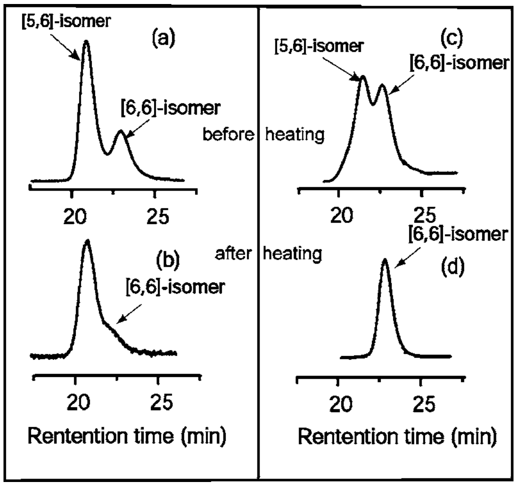

Figure 2. HPLC (Buckyprep-M, toluene eluent at 12 mL/min) profiles of reaction products: (a) $[C_4H_9N]$-$ScGd_2N@C_{80}$, (b) $[C_4H_9N]$-$ScGd_2N@C_{80}$ after 1 h of heating at 180 °C, (c) $[C_4H_9N]$-$Gd_3N@C_{80}$, and (d) $[C_4H_9N]$-$Gd_3N@C_{80}$ after 1 h of heating at 180 °C.

To understand the observed different regioselectivities of $Sc_xGd_{3-x}N@C_{80}$ ($x = 0-3$), all-electron relativistic density functional calculations at the PBE/DNP level of theory[10] were performed to evaluate the relative energy of all [5,6]- and [6,6]-regioisomers. As shown in Table 1, the energetic difference (ΔE) between [5,6]- and [6,6]-adducts is quite large (11.7 kcal/mol) for $Sc_3N@C_{80}$. Along with the encaged M_3N cluster size increasing from Sc_3N to Gd_3N, ΔE decreases to 8.7 kcal/mol for $Sc_2GdN@C_{80}$, 2.3 kcal/mol for $ScGd_2N@C_{80}$, and −0.4 kcal/mol for $Gd_3N@C_{80}$. Clearly, due to the very large size of Gd_3N, an inversed regioselectivity is expected for the pyrrolidino-adducts of $Gd_3N@C_{80}$, which is well in line with the experimental results.

Table 1. PBE/DNP-Predicted Key Geometric Parameters (Bond Length, in Å; Angle in deg) of $Sc_xGd_{3-x}N@C_{80}$ ($x = 0-3$) and Formation Energies (RE, in kcal/mol) of and Energy Differences (ΔE, in kcal/mol) between the [6,6]- and [5,6]-Regioisomers of Pyrrolidinofullerenes

	$Sc_3N@C_{80}$	$Sc_2GdN@C_{80}$	$ScGd_2N@C_{80}$	$Gd_3N@C_{80}$
Sc−N	2.03	1.95	1.90	
Gd−N		2.18	2.11	2.12
Sc−C[a]	2.26	2.22	2.21	
Gd−C[a]		2.46	2.44	2.43
RE				
[6,6]-adduct	−34.1	−38.2	−43.8	−46.2
[5,6]-adduct	−45.8	−46.9	−46.1	−45.8
ΔE[b]	11.7	8.7	2.3	−0.4

[a] The nearest M to C (cage) distance. [b] $\Delta E = E_{tot}$([6,6]-adduct) − E_{tot}([5,6]-adduct).

In summary, our combined experimental and theoretical investigation clearly demonstrates that the regioselectivity of the TNT-based endohedral fullerenes $Sc_xGd_{3-x}N@C_{80}$ ($x = 0-3$) in the exohedral cycloadditions depends remarkably on the size of the encaged cluster, i.e., [5,6]-regioisomers being major products in the $Sc_xGd_{3-x}N@C_{80}$ ($x = 1-3$) cases and [6,6]-regioisomers being major products for the largest $Gd_3N@C_{80}$.

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Supporting Information Available: Details of experiments and computed structures of the pyrrodinofullerenes. This material is available free of charge via the Internet at http://pubs.acs.org.

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(8) We collected the pyrrolidinofullerene fractions of $Sc_3N@C_{80}$ and $Sc_2GdN@C_{80}$ with retention times at 21.4−24.0 min and performed the HPLC again. It can be seen that the former maintains a single peak while the latter sample shows two distinct peaks (Figure S2, Supporting Information) in the HPLC profiles.

(9) The pyrrolidinofullerene fractions of $Gd_3N@C_{80}$ with retention times at 21.4−24.0 min are collected and HPLC was performed again. It shows a minor peak with short retention time appears before the major peak, which was assigned as the [5,6]-$Gd_3N@$pyrrodino-C_{80} regioisomer.

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