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Isolation and Characterization of [5,6]-Pyrrolidino-Sc₃N@I₈-C₈₀ Diastereomers

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Reactions of Sc₃N@I₈-C₈₀ with aziridine derivatives were conducted to afford the corresponding mono-adducts. A pair of diastereomers of the mono-adduct [5,6]-pyrrolidino-Sc₃N@I₈-C₈₀ was isolated and characterized by means of mass spectrometry, Vis-NIR absorption spectroscopy, and X-ray crystallography. The structural characterization of the mono-adducts was conducted by NMR and single-crystal X-ray structure determinations.

Recent developments in the chemistry of endohedral metallofullerenes (EMFs) have led to an increasing effort to elucidate how the chemical reactivity and selectivity of empty fullerenes are changed by endohedral metal doping and how the electronic properties of metallofullerenes affect chemical functionalization. The preparation and isolation of trimetallic nitride template endohedral metallofullerenes (M₃N@C₈₀) in macroscopic quantities have facilitated the study of their structures, properties, and chemical reactivities. To date, the functionalization of Sc₃N@I₈-C₈₀ has been widely performed using Diels-Alder reaction, cycloaddition, carbone addition, hydroxylation, disilane addition, radical addition, azide addition, and so on. 1,3-Dipolar cycloaddition of azomethine ylides is one of the most successful reactions in fullerene chemistry. Azomethine ylides are organic 1,3-dipoles possessing a carbanion next to an immonium ion and can be readily produced upon decarboxylation of the immonium salts derived from the condensation of α-amino acids with aldehydes or ketones. Notably, functionalized aldehydes lead to the formation of 2-substituted fullerylpyrrolidines, whereas reaction with N-substituted glycines leads to N-substituted fullerylpyrrolidines. Recently, the chiral control of fullerylpyrrolidine of C₈₀ was achieved. In this context, the advantages, which come from good yields, the high regioselectivity, and availability or easy preparation of the starting materials in reactions of Sc₃N@I₈-C₈₀, encourage the synthesis of functionalized materials to open the materials science of metallofullerenes.

Alternatively, fullerylpyrrolidines can be obtained via the thermal ring opening of aziridines. Moreover, the addition of aziridines has been extended to carbon nanotubes, which upon thermal reaction with 2-alkoxyacylonylaziridine, afforded the corresponding pyrrolidino-derivatives. Since custom-synthesized aziridines, carrying groups with advanced functionality, can be prepared from commercially available reagents in high yields through only a few steps, the applicability of this kind of functionalization deserves more attention. Herein, we report the synthesis of pyrrolidino-Sc₃N@I₈-C₈₀ from Sc₃N@I₈-C₈₀ and aziridine derivatives as well as the formation and isolation of a pair of diastereomers. In addition, the structural characterization of pyrrolidino-Sc₃N@I₈-C₈₀ was obtained from electronic absorption, NMR spectroscopy and X-ray crystallography, while the redox properties of pyrrolidino-Sc₃N@I₈-C₈₀ were evaluated by electrochemical means.

The reaction of Sc₃N@I₈-C₈₀ with 1a was conducted at 180°C in α-dichlorobenzene (ODCB) for 1 h (Scheme 1). Subsequent preparative HPLC separation afforded products 2a and 3a in 26% and 18% yields, respectively (Figs S1 & S2). The conversion yields of 2a and 3a were calculated from the HPLC peak area assuming that Sc₃N@I₈-C₈₀ and the mono-adducts have the same absorption coefficients. Matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) mass spectra of 2a and 3a clearly displayed the molecular ion peaks at m/z 1267, as expected for the 1:1 adducts of Sc₃N@I₈-C₈₀ and 1a (Figure S3). The fragment peaks were observed at m/z 1109, which corresponded to the mass of the fragment ion (Sc₃N@I₈-C₈₀). Similarly, the reaction of 1b and Sc₃N@I₈-C₈₀ gave two products 2b and 3b in 19% and 24% yields, respectively (Figs S10 & S11).

![Scheme 1. Reaction of Sc₃N@I₈-C₈₀ with 1](image)

There are two possible position isomers (A–D) for 2 and 3 as shown in Fig. 1 because the I₈-C₈₀ cage has two kind of non-equivalent C-C bonds. Mono-adduction occurs at a C-C bond located between a five- and six-membered ring (so-called [5,6]-addition) and the other addition takes place at a C-C bond located between two six-membered rings (so-called [6,6]-addition). When glycine derivatives and aldehydes were used as the starting materials, [5,6]-pyrrolidino-Sc₃N@I₈-C₈₀ was obtained. On the other hand, when N-triphenylmethyl-5-oxazolidinone was used as the...
starting material, [6,6]-pyrrolidino-Sc,N@I-C60, was obtained, as the kinetically controlled product. It was also reported that [6,6]-pyrrolidino-Sc,N@I-C60 is converted thermally to the more thermodynamically stable [5,6]-adduct. As previous studies showed that the UV-vis-NIR absorption spectra of C60 adducts reflected sensitively the addition pattern rather than the nature of the addends, the UV-vis-NIR spectra can be regarded as a power tool to determine the addition pattern in fullerene adducts. [6,6]-N-tritylpyrrolidino-Sc,N@I-C60, [6,6]-Sc,N@I-C60(3H2)NTrt, and benzene [6,6]-adduct of ScN@I-C60, [6,6]-ScN@I-C60(CH3), exhibited the characteristic absorption peak at ca. 800 nm. In contrast, [5,6]-Sc,N@I-C60(3H2) showed weak absorption peaks centered at 950 nm. The absorption spectra of 2 and 3 show the distinctive absorption maxima around 960 nm (2a: 958 nm, 2b: 959 nm, 3a: 959 nm, 3b: 959 nm.). These characteristic absorptions suggest that 2 and 3 are [5,6]-addition products (Fig. S4).

The molecular structure of 2a was determined using X-ray crystallographic analysis. The structural drawing shown in Fig. 2 confirms that the addition took place at the [5,6]-bond. The pyrrole ring is in an envelope conformation in which the nitrogen atom is above the pentagon ring. The alkoxy carbonyl group is located on the hexagon side on the C60 cage (addition pattern: A). Thus, 3a can be assigned to the stereoisomer of 2a, which has the alkoxy carbonyl group located at the pentagon side on the C60 cage (addition pattern: B).

The 1H NMR spectra of 2a and 3a showed protons in the pyrrole rings at 4.81, 4.19, and 4.02 ppm and 4.40, 4.24, and 3.56 ppm, respectively (Fig. S5). The diastereotopic geminal protons of the pyrrole rings appeared at 4.19 and 4.02 ppm (J = 8.8 Hz) in 2a and 4.40 and 3.56 ppm (J = 9.5 Hz) in 3a and are correlated with the carbon atom at 59.8 ppm in 2a and 62.6 ppm in 3a in the HMOC spectra (Figure S8). The 13C NMR spectra of 2a and 3a showed a total of 78 lines assigned to sp2 hybridized cage carbons of ScN@I-C60 (Figure S6). In addition, the sp3 hybridized cage carbons appeared at 62.2 and 57.6 ppm in 2a and 61.8 and 56.4 ppm in 3a, which disappeared in DEPT-135 NMR. (Figure S7). Echegoyen et al. suggested that the large Δδ values for the geminal protons of ScN@I-C60(CH3)NR are mainly due to surface ring currents on the C60 cage. The chemical shift of the methine proton on the pyrrole ring can be used for the simple and concise structural identification of 2-substituted-[5,6]-pyrrolidino-Sc,N@I-C60. It is noteworthy that the 1H NMR signals of methine protons of 2a and 2b in the pyrrole ring appeared downfield compared to those of 3a and 3b, respectively. For the assignment of the 1H NMR, the 1H NMR chemical shifts of 2b and 3b were calculated by the M06-2X-GIAO method. The calculated chemical shift of the methine proton of 2b (4.64 ppm) was lower than that of 3b (3.49 ppm), as shown in Table 1, which strongly supports the structures of 2b and 3b. Furthermore, whereas geminal protons of 3a and 3b in their 1H NMR spectra showed a large Δδ value (Δδ: difference of the chemical shifts of the geminal protons in the pyrrole ring, 3a: Δδ = 0.84; 3b: Δδ = 1.49), 2a and 2b showed a small Δδ value (2a: Δδ = 0.17; 2b: Δδ = 1.68). Thus, the structure of 2b (addition pattern A, the alkoxy carbonyl group located at hexagon side) and 3b (addition pattern B, the alkoxy carbonyl group located at pentagon side) were determined based on the NMR and theoretical calculations.

Dorn et al. reported that [5,6]-Sc-N@I-C60(CH3)NTrt was obtained as the thermodynamically favorable product and [6,6]-ScN@I-C60(CH3)NTrt was obtained as the kinetically favorable product from the reaction of N-triphenylmethyl-5-oxazolidinone via the corresponding azomethine ylide. When an azomethine ylide was prepared from N-alkylglycine and an aldehyde, [5,6]-Sc-N@I-C60(CH3)NR (R: Me or Et) was obtained as a thermodynamically favorable product. The relative energy difference between [5,6]- and [6,6]-ScN@I-C60(CH3)N-CH2CH2CN was calculated using the M06-2X method. The results showed that the [5,6]-adduct is the thermodynamically favorable product (Fig. S21). Therefore, 2 and 3 were obtained as the thermodynamically preferred mono-adducts under the reflux conditions in ODCB.

The redox properties of 2 and 3 were determined from the results of cyclic (CV) and differential pulse voltammetry (DPV) measurements (Table 2 & Fig. S20). Compounds 2 and 3 exhibited three reversible reduction and two quasi-reversible oxidation patterns. The reversible cathodic behavior of 2 and 3 is consistent with previously reported results for [5,6]-pyrrolidino-M,N@I-C60 derivatives. The identical electrochemical behavior of 2 and 3 indicates that the position of the alkoxy carbonyl group in 2 and 3 does not affect the electronic property of pyrrolidino-Sc,N@I-C60.
Notes and references

Graphical abstract

Reactions of Sc3N@Ih-C80 with aziridine derivatives afforded a pair of diastereomers of the mono-adduct [5,6]-pyrrolidino-Sc3N@Ih-C80. Structural analysis of the mono-adducts was conducted by NMR and single-crystal X-ray structure determinations.