Fullerenes

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Nitrated Benzyne Derivatives of La@C_{82}: Addition of NO_2 and Its Positional Directing Effect on the Subsequent Addition of Benzynes**

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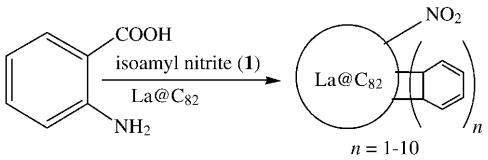
Endohedral metallofullerenes (EMFs), that is, fullerenes with metal atoms or metallic clusters trapped inside their hollow interiors, have a variety of fascinating properties and promising applications in many fields, such as biomedicine, electronics, and materials science.[1–4] Since the first reported synthesis of exohedral adducts of EMFs,[5] chemical modification of EMFs has attracted significant attention because of the potential to tune the properties of the EMF by attaching different functional groups onto the external cage, thereby affording derivatives that are more synthetically useful than the parent EMFs.

Although the chemical investigation of EMFs has been less widely reported than that of empty fullerenes, various EMF derivatives have been synthesized and thoroughly characterized during recent years.[1–19] Cycloadduct derivatives of EMFs that contain closed five- or six-membered rings between the substituent and the fullerene cage have been synthesized using, for example, 1,3-dipolar additions or Diels–Alder reactions.[6–8] In contrast, the formation of three-membered rings typically results in an opening of the fullerene cage, thus affording open structure derivatives. Representative examples are the Bingel adducts of $Y_3N@C_{80}$[9] and the adamantylidene EMF derivatives.[10–15] This difference in stability cannot be explained simply by the higher ring-strain in a cyclopropyl ring, because the Bingel adducts of $Sc_3N@C_{78}$ have closed structures.[16] There are few reports of singly bonded derivatives of EMFs; some recent examples include the benzyl adducts of La@C_{82}[17] and $Sc_3N@C_{80}$.[18] However, the synthesis and characterization of EMF derivatives that have four-membered rings has not yet been achieved.[19] It has long been expected that EMFs would have different chemical properties to empty fullerenes owing to the presence of the metal core which has strong interactions with the carbon shell; however, such findings are rare.[17] Herein, we report the [2+2] cycloaddition of benzyne to La@C_{82} as an example of EMFs that show significantly different properties to hollow fullerenes; that is, the unexpected addition of an NO_2 group to La@C_{82} was observed, which exerts a positional directing effect on the addition sites of benzynes. The benzyne groups selectively add to the [5,6]-bonds of La@C_{82} to form closed cyclobutenyl structures (Scheme 1).



Scheme 1. Reaction of La@C_{82} with anthranilic acid and isoamyl nitrite (**1**).

Benzyne is generated by the diazotization of anthranilic acid with isoamyl nitrite (**1**),[19] which reacts in situ with La@C_{82}. Multiple adducts are unavoidable, even at 0 °C (Supporting Information, Figure S1). MALDI-TOF spectrometry of the reaction mixture showed that the C_{82} cage can be derivatized with up to 10 benzene addends (Figure 1). Surprisingly, molecular ion peaks ascribed to La@C_{82}-$(C_6H_4)_nNO_2$ are also clearly visible, but no peaks of adducts that contain more than one NO_2 group are detected. As well as the two sets of mass peaks corresponding to La@$C_{82}(C_6H_4)_n$ and La@$C_{82}(C_6H_4)_nNO_2$, signals corresponding to [La@C_{82}-$(C_6H_4)_n+O$] or [La@$C_{82}(C_6H_4)_n+N$], and [La@C_{82}-$(C_6H_4)_nNO_2+O$] are also observed, which are generated either by detachment of one or two of the NO_2 group oxygen atoms from the cage, or by recombination of La@$C_{82}(C_6H_4)_n$ or La@$C_{82}(C_6H_4)_nNO_2$ with oxygen atom fragments in the spectrometer chamber. For clarity, these peaks are not marked in Figure 1.

Furthermore, following elimination of unreacted La@C_{82} by HPLC, the mixture of adducts (fractions between 5 min

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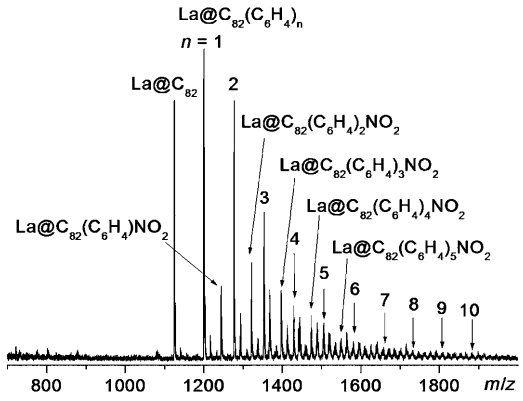


Figure 1. MALDI-TOF mass spectrum of the reaction mixture.

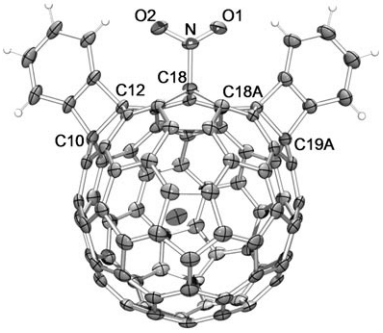


Figure 3. An ORTEP drawing of **2** with ellipsoids set at 50% probability level. The CS_2 and hexane molecules are omitted for clarity.[20]

and 30 min; Supporting Information, Figure S1) shows no ESR signal (Figure 2), which indicates that: 1) the NO_2 group links to the carbon cage by a single bond and quenches the

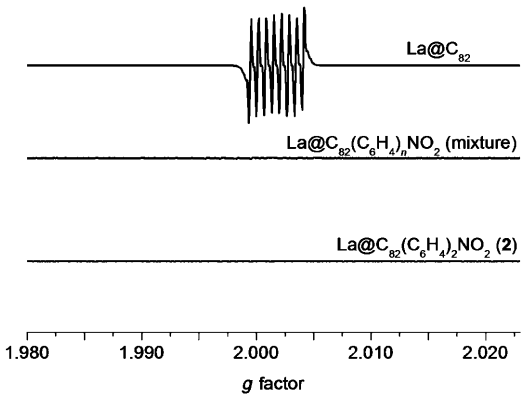


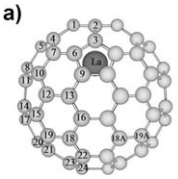
Figure 2. ESR spectra of La@C_{82}, the mixture of adducts, and **2**.

paramagnetic character of pristine La@C_{82}, and that 2) all of the adducts contain only one NO_2 group. Finally, a trisadduct was isolated which contained two benzene rings and one NO_2 group, La@$C_{82}(C_6H_4)_2NO_2$ (**2**). This trisadduct was characterized using various experimental techniques, including single-crystal X-ray diffraction. This is not only the first reported EMF trisadduct, but also the first EMF derivative that contains substituents which are both singly and cyclically bound to the cage framework.

The MALDI-TOF spectrum of **2** shows a pronounced peak at *m*/*z* 1276, ascribed to La@$C_{82}(C_6H_4)_2$, which confirms the successful attachment of two benzene rings (Supporting Information, Figure S2). Absence of the molecular ion peak of **2** reflects that the NO_2 group is singly bonded to the cage, and can thus be easily removed using laser irradiation. The single bond is consistent with the ESR-silent property of **2** (Figure 2).

The molecular structure of **2** has been confirmed using single-crystallographic X-ray spectrometry (Figure 3).[20] The three addends are bound to cage carbon atoms far from the lanthanum atom, such that the position of the metal is not obviously changed by the addition. Whereas the benzyne derivatives of C_{60} are all [6,6]-adducts,[21] both benzene moieties in **2** add to the [5,6] ring fusions of La@C_{82}. The bond lengths of C10–C12 and C18A–C19A (both 1.64 Å) confirm a closed structure of **2**. Therefore, the [5,6]-bonds have more double-bond character than [6,6]-bonds in La@C_{82}. The NO_2 group is singly bonded to a [566]-ring junction (C18), which has been pulled outward from its normal position. The N–C18 bond length is 1.55 Å, and the respective N–O1 and N–O2 distances are 1.19 Å and 1.27 Å.

Spin densities (SDs) and π-orbital axis vector (POAV) values[22] of La@C_{82} were calculated to elucidate the addition patterns in the formation of **2** (Figure 4; Supporting Information, Figure S3).[17] The addition site of NO_2 is C18, which has both a high spin density (0.03) and a high POAV value (11.0). Accordingly, the C18 position is expected to be particularly reactive toward radicals. Recently, our group found that La@C_{82} can even undergo a radical coupling reaction with toluene;[17] therefore, it is not surprising that La@C_{82} preferentially reacts with trace NO_2 radicals of **1**. As the presence of a nitro group facilitates nucleophilic aromatic substitution, the resulting La@$C_{82}NO_2$ species would evidently favor the subsequent addition of benzyne; this proposed pathway is supported by the absence of the molecule ion peak of La@$C_{82}NO_2$ in Figure 1. Addition sites of the two benzyne moieties are C10–C12 and C18A–C19A, respectively, which all have high POAV values (Supporting Information, Figure S3). This postulation is consistent with the reported higher reactivity of the pyramidalized carbons of C_{70} to benzyne.[23] After the addition of NO_2, calculations on [18]NO_2-La@C_{82} show that C10, C12, C18A, and C19A all



b)

	C10	C12	C18	C19
POAV	10.7	10.9	11.0	10.9
SD	0.03	0.00	0.03	0.02

Figure 4. a) Optimized structure of La@C_{2v}-C_{82} with the 24 non-equivalent carbons labeled numerically. C18A and C19A are also shown for comparison purposes. b) SD and POAV values of selected carbons of La@C_{2v}-C_{82}.

retain their high POAV values, although the values of other carbon atoms adjacent to C18 become lower (Supporting Information, Figure S3). In particular, C12 and C18A have even higher POAV values than in the pristine La@C_{82}; they are therefore certainly reactive toward benzyne. As C12 and C18A are both situated at 1,4-positions relative to the NO_2-appended C18 position, it is thought that the NO_2 group has a positional directing effect on the subsequent addition of the two benzyne substituents.

The UV/Vis–NIR spectrum of **2** shows three broad absorption bands at approximately 520 nm, 710 nm, and 860 nm. It differs entirely from that of pristine La@C_{82}, which has two sharp absorption peaks at approximately 640 nm and 1000 nm, with a further broad band at 1430 nm (Figure 5). This discrepancy confirms that the electronic structure of La@C_{82} has been significantly altered by the addition of the three substituents.

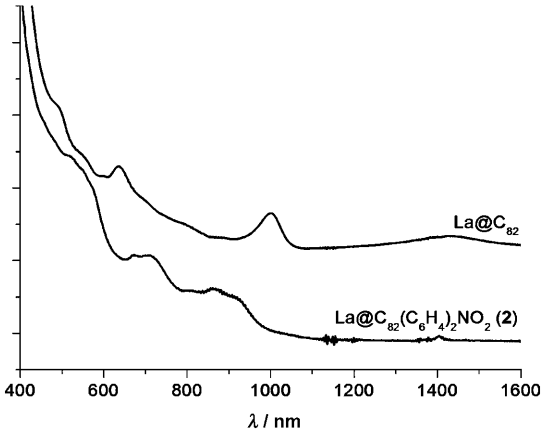


Figure 5. UV/Vis–NIR spectrum of La@C_{82} and **2**.

The electrochemical properties of **2** show less difference with those of La@C_{82}. The reduction potentials of **2** resemble the corresponding values of La@C_{82}, but the oxidation potential of **2** is 0.18 V more positive than the value of La@C_{82} (Table 1). As the nitro group is known to be highly electron-withdrawing, it is reasonable to speculate that the anodical shift is caused mainly by the addition of the nitro group, rather than the two benzene groups. Our previous results have shown that reduction of EMFs is attainable by the addition of disilirane[5] or admantylidene.[10–15] The results presented herein suggest that oxidation of EMFs can be performed successfully by addition of a nitro group. These results are useful for the synthesis of EMF derivatives for potential applications in photovoltaics and electronics.[2,4]

Table 1: Redox potentials of La@C_{82} and **2**.[a]

Compound	$^{ox}E_1$	$^{red}E_1$	$^{red}E_2$
La@C_{82}	+0.07	−0.42	−1.34
2	+0.25	−0.39	−1.39

[a] Potentials in V vs. Fc/Fc^+. Differential pulse voltammetry determined in 1,2-dichlorobenzene with 0.1 M $(n\text{Bu})_4NPF_6$ at a platinum working electrode.

In conclusion, we present the first preferential addition of benzyne to the [5,6]-bond of La@C_{82} to form closed cyclobutene rings between the substituents and the cage. Unexpectedly, an NO_2 group was also found in the benzyne adducts that has an oxidation effect on the electrochemical properties of La@C_{82}. Although benzyne usually reacts with highly pyramidalized carbons, the nitro group adds to a cage carbon which has both a high POAV value and a high spin density. It is particularly interesting that the three addends apparently prefer a 1,4-addition pattern, which implies a positional directing effect of the NO_2 group. Our results, which present valuable information for elucidating the structures and properties of EMFs, will be useful in future work for investigating the synthesis of EMF-based materials.

Experimental Section

La@C_{82} was synthesized by an improved direct current arc-discharge method and isolated by HPLC. The purity is estimated to be higher than 99% by mass spectrometry, ESR and HPLC analysis. Anthranilic acid and isoamyl nitrite were bought from TCI and used as received.

Typical procedure: N_2 gas was bubbled for 20 min through a toluene solution (40 mL) containing both La@C_{82} ($M_r = 1123$, 4.0 mg, 8.90×10^{-5} M) and isoamyl nitrite (**1**, $C_5H_{11}NO_2$, $M_r = 117$, 6.0 μL, 1.11×10^{-3} M) in a flask within an ice-trap. Anthranilic acid ($C_7H_7NO_2$, $M_r = 137$, 6.0 mg, 1.09×10^{-3} M) was then added under vigorous stirring. The reaction proceeded smoothly at room temperature under a stream of N_2, and was followed by HPLC (analytical Buckyprep column; Φ 4.6 mm × 250 mm). As nitro compounds are explosive and poisonous, all the reactions were performed under a stream of N_2, rather than in sealed tubes, without incident. After stirring for 8 h, the reaction was stopped; the mixture was concentrated and filtered for HPLC separation, which gave the trisadduct La@$C_{82}(C_6H_4)_2NO_2$ (**2**) in approximately 15% yield, based on consumed La@C_{82}.

Preparative HPLC was conducted on an LC-908 machine (Japan Analytical Industry Co., Ltd) with toluene as the mobile phase. MALDI-TOF MS was performed on a BIFLEX III (Bruker, Germany) with 1,1,4,4-tetraphenyl-1,3-butadiene (TPB) as a matrix. UV/Vis–NIR spectra were measured on a UV 3150 machine (Shimadzu, Japan) in CS_2. Differential pulse voltammogram (DPV) analysis was performed in 1,2-dichlorobenzene with 0.1 M $(n\text{Bu})_4NPF_6$ at the platinum working electrode, on a potentiostat/galvanostat workstation (BAS CW-50).

Single crystals of **2** were obtained by layering a CS_2 solution under hexane. X-ray intensity data were collected on a Rigaku DSC imaging plate system using monochromatic silicon synchrotron radiation (λ = 1.00000 Å) at beam line BL-1 A of Photon Factory (PF), High-Energy Accelerator Research Organization (KEK, Japan). CCDC 745648 (**2**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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