Differentiation of Isomers Resulting from Bisaddition to C_{60} Using ^{3}He NMR Spectrometry

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Abstract: ^{3}He NMR spectrometry has been used to examine bisaddition to C_{60} containing an encapsulated ^{3}He atom (^{3}He@C_{60}) using three types of reactions: (1) cyclopropanation with diethyl bromomalonate and base to give dicarbethoxymethanofullerenes (Bingel−Hirsch reaction), (b) addition of azomethine ylides to give *N*-methyl-fulleropyrrolidines (Prato−Wudl reaction), and (c) reduction to give $C_{60}H_4$. ^{3}He NMR spectra of crude reaction mixtures in all three series showed well-separated resonances for each of the bisadducts, spread out over more than 2 ppm. The major isomeric bisadducts from the first two reactions were separated and characterized, and the ^{3}He NMR spectra of the individual major bisadducts from ^{3}He@C_{60} were obtained (five isomers from reaction 1, four isomers from reaction 2). Although the absolute chemical shifts in the two series of bisadducts differ, the relative chemical shifts are significantly but not perfectly correlated. Bisadducts with appended ligands on opposite hemispheres of C_{60} (**7**, **6**, and **5**) tend to have ^{3}He NMR resonances downfield of the bisadducts with appended ligands on the same hemisphere (bisadducts **2** and **3**). Unfortunately, the equatorial isomer **4**, a major product from the Hirsch addition reaction, was not obtained in sufficient quantity for study from the Prato reaction. Well-separated resonances were also seen for the isomeric compounds of composition ^{3}He@$C_{60}H_4$ from reaction of the fullerene with diimide, but the individual isomers were not separated. The very large differences in the ^{3}He NMR chemical shifts of the isomeric bisadducts in all three reactions demonstrate that the magnetic field felt by the ^{3}He atom due to the ring currents in the residual π-system is extremely sensitive to the pattern of ligation on the C_{60} surface. These results provide further support for the assertion that ^{3}He NMR is a very sensitive probe of patterns of chemical addition to fullerenes, and suggest that this technique will prove to be generally useful in determining the ratio as well as the identity of isomeric fullerene bisadducts.

Introduction

Buckminsterfullerene (C_{60}) is the parent compound in the new field of three-dimensional aromatic chemistry. It therefore has a place similar to that of benzene in the older two-dimensional aromatic chemistry. While substitution reactions of benzene and higher homologues generate a vast number of known aromatic compounds, the fullerenes, having no hydrogens to substitute, typically undergo addition reactions to form functionalized derivatives. Many reagents which add to double bonds also add readily to fullerenes, and a large number of adducts are already known.[1] Most of the products result from addition across bonds shared by two six-membered rings (6,6 adducts).[1] Thus, reduction of C_{60} by hydroboration or hydrozirconation yields only one dihydro adduct in which the hydrogens are on adjacent carbons on a 6,6 ring fusion,[2] although in principle addition of H_2 could occur to yield 23 isomers of $C_{60}H_2$.

Addition of a single moiety to C_{60} (effectively removing one of the thirty formal double bonds) does not deactivate it for

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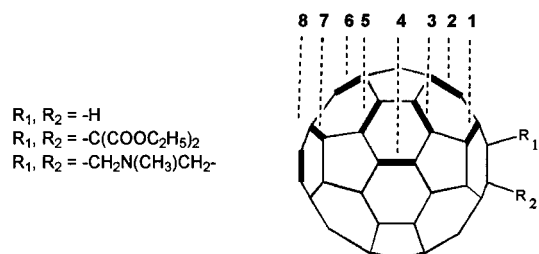
Figure 1. Numbering system for isomeric bisadducts derived from addition of a symmetrical ligand across [6,6] bonds of C_{60}.

further addition. Excess reagent results in multiaddition with formation of bisadducts, trisadducts, etc. Monoadducts are normally prepared by using less than 1 equiv of reagent followed by chromatographic separation of the product from unreacted starting material and multiple adducts. While *ortho*, *meta*, and *para* disubstitution of benzene can occur, there are eight possible 6,6 bisadducts of C_{60} when the same symmetrical addend is attached[1] (see Figure 1 for a structural descriptor with the numbering scheme used in this paper). There are 44 possible 6,6 trisadducts and 216 possible tetrakisadducts. At this time, workers in this field are just learning how to separate and identify the isomers from multiaddition to C_{60}. Even larger numbers of isomers are possible from additions to C_{70}.[3]

Reduction beyond the dihydro stage gives a very complex mixture of isomers of $C_{60}H_4$ according to ^{1}H NMR, of which only 1,2,3,4-$C_{60}H_4$ has been conclusively identified.[4] The structures of five products from bisosmylation of C_{60} were assigned by Hawkins (two firmly, three tentatively)[5] using a

combination of 1D ^{1}H NMR and 1D and 2D ^{13}C NMR using ^{13}C-enriched C$_{60}$. More recently, the structures of seven of the eight possible isomeric bromomalonate bisadducts of C$_{60}$ were assigned by Hirsch[6] on the basis of their molecular symmetries as indicated by ^{1}H and ^{13}C NMR spectra, along with calculated dipole moments and HPLC elution times. However, such assignment strategies are not general, are usually inconvenient, and often leave some residual ambiguities.[6]

Noble gas atoms have been introduced into fullerenes by heating them under a high pressure of the gas.[7] If this process is carried out at 620 °C using ^{3}He at 3000 atm, enough ^{3}He can be introduced inside the fullerenes to allow observation of ^{3}He NMR spectra.[8,9] Very sharp peaks are measured with respect to dissolved ^{3}He. ^{3}He NMR is a probe of the magnetic field inside the fullerene cage, which is affected by ring currents of the π-electrons which are altered in C$_{60}$ adducts. Thus far, each product made from ^{3}He-labeled fullerenes has yielded a distinct sharp peak in the ^{3}He NMR spectrum.[9−12] Derivatization of the fullerenes changes the π-structure of the cage and alters the magnetic field felt by the ^{3}He nucleus inside, producing marked changes in the ^{3}He chemical shifts relative to those in parent fullerenes. No extraneous peaks arise from reagents, non-fullerene products, solvent, or other impurities. In a short period, ^{3}He NMR spectroscopy has become an important tool in the characterization of fullerenes and their derivatives.[13]

C$_{60}$H$_2$ and a variety of cycloadducts with four-, five-, and six-membered rings fused to the fullerene core all show slightly different ^{3}He shifts around 3 ppm upfield from that of ^{3}He@C$_{60}$.[13] These differences may be due to direct effects of these groups on the magnetic field in the center of the fullerene or to indirect effects resulting from slight alteration of the remaining fullerene π-system. In contrast, the bisadducts previously reported[11] and those described in this paper have ^{3}He chemical shifts which span a much wider range. The ^{3}He chemical shifts of C$_{60}$ epoxide and methanofullerenes are unusual in that they are only ~2 ppm upfield of that of C$_{60}$.[12] The π-character of the three-membered rings causes these adducts to be more similar to the fullerene. The wide range of

chemical shifts in the bisadducts suggests that ^{3}He NMR spectroscopy is potentially a powerful general method for identification of isomeric C$_{60}$ adducts, which was further explored in the present study.

Results and Discussion

We examined the biscyclopropanation of C$_{60}$ with diethyl bromomalonate (eq 1) which has been investigated systematically by Hirsch *et al.*[6b] Seven isomeric bisadducts C$_{62}$(CO$_2$Et)$_4$

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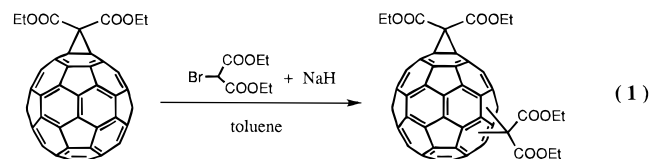
were isolated and characterized as in Hirsch's study.[6b] When we subjected ^{3}He@C$_{60}$ to the Bingel−Hirsch reaction[6] under conditions which optimized bisadduct formation, each product component displayed its own characteristic ^{3}He NMR chemical shift in the spectrum of the total reaction mixture (Figure 2) as anticipated. On the basis of comparison of the peak area ratio in the ^{3}He NMR spectrum with the peak areas observed on HPLC analysis of the reaction mixture (see inset, Figure 2), some tentative peak assignments could be made. Thus, the peak at −6.4 ppm corresponds to ^{3}He@C$_{60}$, and that at −8.1 is due to the monoadduct. The large peaks at −8.7, −9.2, −9.7, and −9.9 ppm can be assigned to the major bisadducts **5, 7, 6**, and **4** (see Figure 1). The smaller peaks at −10.2, −10.5, −11.0, and −12.0 ppm are assigned to the minor bisadducts **2, 3**, and **8** as well as trisadducts.

To obtain definitive peak assignments, the mixture of ^{3}He@C$_{60}$ adducts was subjected to semipreparative silica HPLC to separate the monoadduct and five bisadducts **3−7**. The individual adducts were identified by comparison of their NMR (^{1}H and ^{13}C) and UV spectra with spectra reported by Hirsch.[6] The ^{3}He NMR spectrum of each of the five pure isomers of ^{3}He@C$_{62}$(CO$_2$Et)$_4$ was then obtained, allowing assignment of the ^{3}He NMR peaks as shown in Figure 2 (for ^{3}He NMR spectra of the individual isomers, see Figures 6−10 in the Supporting Information). Using an additional equivalent of diethyl bromomalonate, isomer **4** was converted to the eq, eq, eq trisadduct **4**−**4**−^{3}He@C$_{63}$(CO$_2$Et)$_6$ as reported by Hirsch.[6c] The ^{3}He NMR peak at −10.2 ppm could then be assigned to **3** and the peak at −12.0 ppm to the **4**−**4** trisadduct. We suspect that the two smaller peaks at −10.5 and −11.0 ppm are due to additional trisadducts. Because of their low yields (<1%), peaks corresponding to bisadducts **2** and **8** are not visible above the background noise.

In order to establish the applicability of ^{3}He NMR for rapid determination of relative yields of isomeric bisadducts in other cases, the azomethine ylide addition reaction (eq 2) of Prato[14]

$$\text{(2)}$$
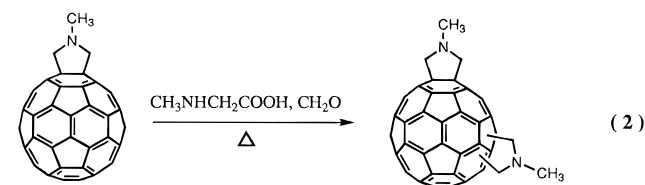
was repeated on ^{3}He@C$_{60}$, to give a mixture of mono-, bis-, and trisadducts, as shown by electrospray MS.[15] The ^{3}He NMR

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(11) Saunders, M.; Jiménez-Vázquez, H. A.; Bangerter, B. W.; Cross, R. J.; Mroczkowski, S.; Freedberg, D. I.; Anet, F. A. L. *J. Am. Chem. Soc.* **1994,** 116, 3621.

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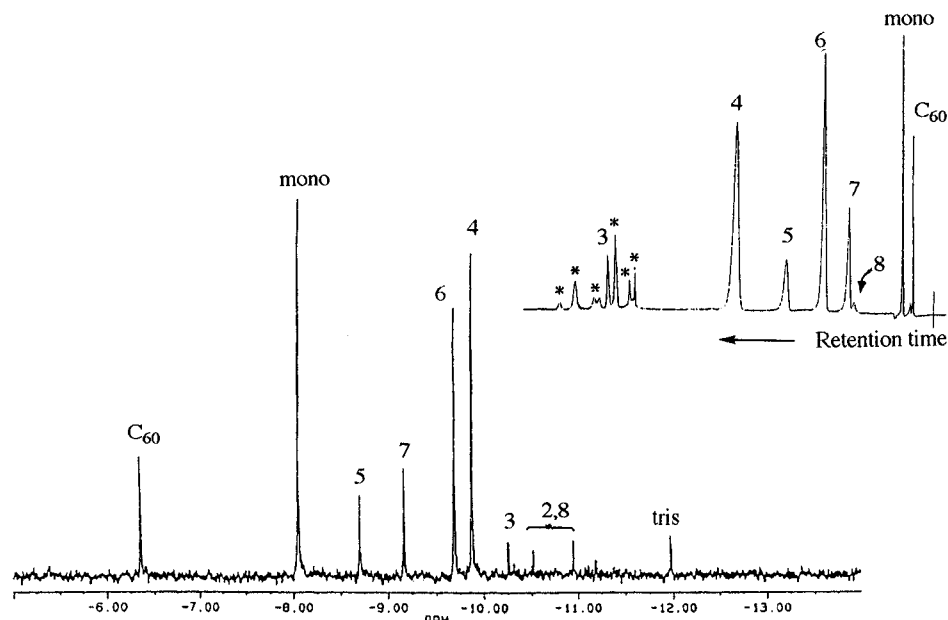(13) Saunders, M.; Cross, R. J.; Jiménez-Vázquez, H. A.; Shimshi, R.; Khong, A. *Science* **1996**, 271, 1693.

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Figure 2. (Bottom) ^{3}He NMR spectrum of the Hirsch reaction mixture from ^{3}He@C$_{60}$ (eq 1). The peaks due to unreacted C$_{60}$, monoadduct, the major bisadducts, and the **4**−**4** trisadduct are marked. (Top) HPLC trace of the Hirsch reaction mixture. Identified components are labeled. Unidentified components are marked with an asterisk. HPLC conditions: 250 × 4.6 mm Adsorbosphere Silica 5μ column. Mobile phase: toluene and then 200:1 toluene/ethyl acetate at 1 mL/min. UV detection at 340 nm. Retention time increases from right to left.
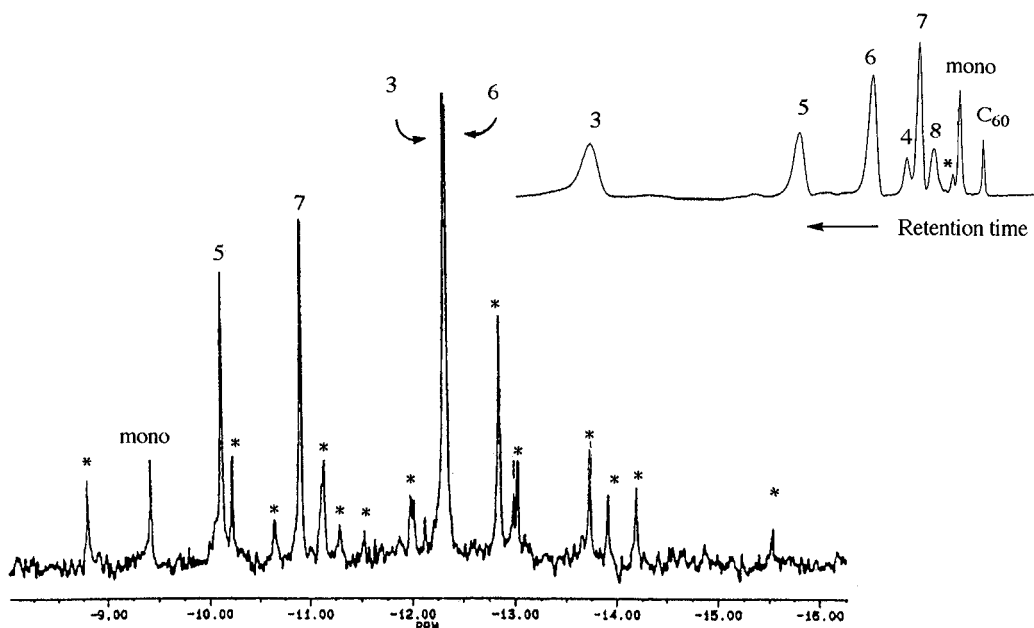

Figure 3. (Bottom) ^{3}He NMR spectrum of the Prato reaction mixture (eq 2) containing mono-, bis-, and trisadducts. Peaks due to identified products are marked. Unassigned peaks are marked with an asterisk. (Top) HPLC trace of the crude Prato reaction mixture on ^{3}He@C$_{60}$. Identified components are labeled. Unidentified components are marked with an asterisk. HPLC conditions: 250 × 4.6 mm Adsorbosphere Silica 5μ column. Mobile phase: toluene and then 1000:2:1 toluene/triethylamine/ethyl acetate at 1 mL/min. UV detection at 340 nm. Retention time increases from right to left.

spectra of a mixture of the monoadduct and two unidentified bisadducts from this reaction were reported earlier.[11] The ^{3}He NMR spectrum of the reaction mixture shown in Figure 3 shows at least 22 signals. The HPLC of the same mixture is shown in the inset to Figure 3. Four of the six major bisadducts were separated by HPLC, and were characterized as isomers **3, 5, 6,** and **7** (see Figure 1) on the basis of their ^{1}H and ^{13}C NMR spectra[16,17] and comparison of their UV spectra with those of the corresponding Hirsch bisadducts. The ^{3}He NMR spectra of each of these compounds (see Figures 11−14 in the

Supporting Information) allowed assignment of the major ^{3}He resonances to the individual bisadducts as shown in Figure 3. Isomer **5** has a chemical shift of −10.14 ppm, while **7** appears at −10.92 ppm. In the mixture, the ^{3}He peaks for **3** and **6** overlapped. The isolated components showed chemical shifts at −12.33 ppm for isomer **3** and −12.36 ppm for isomer **6**, respectively. To confirm these assignments, a small amount of **6** was added to pure **3**, and indeed the peak corresponding to **6** appeared slightly upfield.

Although all of the Prato bisadducts (eq 2) have their resonances upfield of those of the corresponding Hirsch bis-adducts (eq 1), there are noteworthy correlations with respect

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to the relative chemical shifts of the respective isomers. In the Hirsch series, the order of the shifts is **5** < **7** < **6** < **4** < **3**, while in the Prato series the order is **5** < **7** < (**6, 3**). In the Hirsch series, the ^{3}He shifts for isomers **5, 6,** and **7** (*trans* bisadducts with appended ligands on opposite hemispheres of C$_{60}$) are clearly downfield of those for isomers **2** and **3**, in which the appended ligands are *cis*, i.e., on the same hemisphere. In the Prato series, ^{3}He shifts for isomers **5** and **7** are again downfield of that of **3** (which is barely downfield of that of **6**), but the assignment for isomer **2** remains uncertain. In both series, the ^{3}He peak for isomer **5** is clearly the furthest downfield followed by that for isomer **7**. The peak for **7** is upfield of that for **5** by 0.5 ppm in the Hirsch series and 0.8 ppm in the Prato series. Larger upfield shifts are seen with isomers **3** (1.5 and 2.2 ppm) and **6** (1.0 and 2.2 ppm) in the two series, respectively.[18] Unfortunately, the equatorial isomer **4**, a major product from the Hirsch addition reaction, was not obtained from the Prato reaction in sufficient quantity for study using ^{3}He NMR. A larger spread in chemical shifts in the Prato series than in the Hirsch series was anticipated, since the cyclopropane bonds in the Hirsch adducts have considerable double bond character. Thus, the Hirsch adducts are more similar to unperturbed C$_{60}$ than are the Prato adducts.[12]

We have also applied ^{3}He NMR spectroscopy to the isomers of C$_{60}$H$_4$.[19] Reduction of C$_{60}$H$_2$ using diimide produces a number of isomers of C$_{60}$H$_4$.[4] Only 1,2,3,4-C$_{60}$H$_4$ (formed in ~50% yield) has been positively identified by Cahill and co-workers from its ^{1}H NMR spectrum; assignment of the several additional AB quartets in this spectrum to other isomers of C$_{60}$H$_4$ has not yet been made.[4] Using a higher-yield method for reduction of C$_{60}$ utiliziing diimide generated by thermolysis of tosylhydrazone,[20] a complex ^{1}H NMR spectrum of the product mixture similar to that previously reported[4] was observed. In contrast, the ^{3}He NMR spectrum shows a well-separated collection of singlets for each product (Figure 4). C$_{60}$H$_2$ appears at −9.2 ppm, and at least six signals are seen in the region −10.3 to −12.8 ppm corresponding to isomers of ^{3}He@C$_{60}$H$_4$ (for a closer view of this region of the ^{3}He NMR spectrum, see Figure 5 in the Supporting Information). The intensity of the ^{3}He NMR signals is consistent with the isomer ratios derived

Figure 4. (A) ^{3}He NMR spectrum for ^{3}He@C$_{60}$H$_2$ produced by hydroboration. The signal at −6.345 ppm is for C$_{60}$ and that at −9.663 ppm for ^{3}He@C$_{60}$H$_2$. (B) ^{3}He NMR spectrum of the reaction mixture produced by diimide reduction of ^{3}He@C$_{60}$. In addition to the peaks seen in spectrum A, there are six signals between −10.30 and −12.79 ppm attributed to isomers of ^{3}He@C$_{60}$H$_4$. A blowup of this region is included in the Supporting Information.

from the ^{1}H NMR spectrum and HPLC analysis of the crude reaction mixture. The range of chemical shifts of the isomers of ^{3}He@C$_{60}$H$_4$ is strikingly similar to that of the isomeric Prato bisadducts. However, we are not yet able to assign the various ^{3}He signals to specific isomers of C$_{60}$H$_4$.

It should be noted that the very large differences in ^{3}He chemical shifts of bis-isomers in these three systems, ranging over several parts per million, are in contrast to the much smaller differences (<0.1 ppm) observed for diastereomeric 6,6 monoadducts, such as *cis*- and *trans*-fused [2 + 2] photoadducts of cyclic enones to C$_{60}$.[21] The large range of ^{3}He NMR chemical shifts of bisadducts in the three systems discussed in this paper is attributed to subtle variations in the ring currents on the fullerene surface due to changing patterns of ligation. Assuming that similar correlations of structure and ^{3}He chemical shifts will be observed with other types of C$_{60}$ bisadducts, it may well prove to be possible in the future to assign structures to bisadducts of C$_{60}$ directly from their ^{3}He NMR spectra. This would be particularly useful in addition reactions utilizing unsymmetrical ligands where regiochemistry becomes an issue, as well as in reactions in which different ligands are added sequentially. Studies in progress are addressing these issues.

Experimental Section

General Information. The high-pressure labeling with ^{3}He was carried out at about 51 000 psi at 620 °C for 5 h. ^{1}H NMR spectra in CDCl$_3$/CS$_2$ were measured on a Varian Gemini-200 spectrometer. UV/vis spectra were obtained on a Perkin-Elmer Lambda 5 UV/vis

(16) The structures of the Prato bisadducts **3, 6,** and **7**, which have C_2 symmetry and consequently display similar ^{1}H NMR spectra, could be assigned by comparison of their UV/vis spectra in the 400−700 nm region and their order of chromatographic elution with corresponding properties of bisadducts produced in the Bingel−Hirsch reaction.[1,6] The adduct **3** is defined by its relatively long elution time as well as its UV spectrum, while structure assignments for **6** and **7**, which show similar ^{1}H NMR spectra, depend on elution times as well as UV spectra. The equatorial bisadduct **4** is uniquely defined by its ^{1}H NMR spectrum, which should show one singlet for the *N*-methyl groups and two singlets and a doublet of doublets for the methylene groups. Adduct **5** is uniquely defined by its ^{1}H and ^{13}C spectra, compatible with its C_s symmetry. The ^{13}C spectrum of **5** shows 35 signals (30 sp^2 fullerene carbons between 155 and 128 ppm, 2 sp^3 fullerene carbons at 69.81 and 69.58 ppm, 2 CH$_2$ groups at 70.05 and 69.39 ppm and 1 methyl group at 41.38 ppm). Complete details regarding the structure assignments for these and other Prato bisadducts of C$_{60}$ are given in ref 17.

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(18) It is interesting that a deshielding effect is also seen in the ^{1}H NMR spectra of the Prato and Hirsch bisadducts, in that the order of the chemical shifts of the methylene and *N*-methyl protons in the bisfulleropyrrolidines and the methyl and methylene proton resonances in the Hirsch bisadducts is **7** < **6** < **5** < **4** < **3**.[17] While there is not a perfect correlation, it is striking that ^{1}H resonances for groups on the outside of the fullerene and resonances for ^{3}He on the inside both tend to be at lower field in *trans* isomers (**8, 7, 6,** and **5**) than in equatorial (**4**) and *cis* isomers (**3** and **2**). Whether such a correlation is general and can be attributed to the same perturbation of the fullerene π-system remains to be established.

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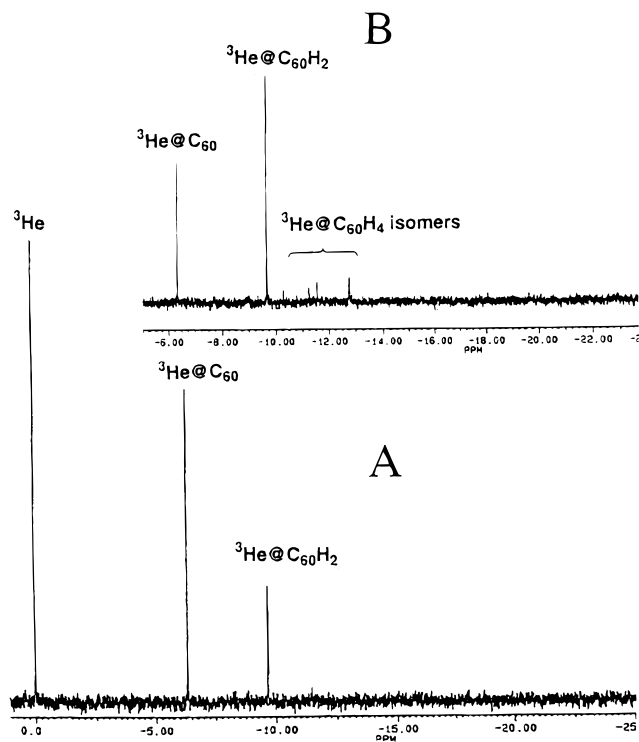
(21) (a) Schuster, D. I.; Cao, J.; Kaprinidis, N.; Lem, G.; Wang, H.; Wu, Y.; Courtney, S. H.; Jiménez-Vázquez H. A.; Saunders, M.; Wilson, S. R. *Proc. Electrochem. Soc.* **1994**, *94-24*, 932. (b) Schuster, D. I.; Cao, J.; Kaprinidis, N.; Wu, Y.; Jensen, A. W.; Lu, Q.; Wang, H.; Wilson, S. R. *J. Am. Chem. Soc.* **1996**, *118*, 5639.

spectrophotometer. Electrospray ionization mass spectra (ESI-MS) were taken on a Vestec Model M-20 single quadrupole mass spectrometer. ^{3}He NMR spectra were obtained on a Bruker AM-500 NMR spectrometer using a 9 ms pulse and 1 s delay between pulses. The samples were dissolved in a mixture of 1-methylnaphthalene and CD$_2$-Cl$_2$ (about 4:1). A small amount of Cr(acac)$_3$ was added to speed relaxation, and about 0.25 mL of ^{3}He gas was bubbled through the solution to act as the reference. A line-broadening factor of 2 Hz was used. Flash chromatography was performed using Merck silica gel 60, 230−400 mesh. Semipreparative HPLC was performed using a 250 × 10 mm Econosil Silica column obtained from Alltech, Inc. HPLC analysis was performed using a 250 × 4.6 mm Adsorbosphere Silica 5μ column obtained from Alltech, Inc. Commercial reagents were used as received. C$_{60}$ (>99%) was purchased from MER Corp.

Preparation of C$_{61}$(CO$_2$Et)$_2$.[6] To a solution of C$_{60}$ (270 mg, 0.37 mmol) in 150 mL of toluene were added NaH (53 mg, 2.2 mmol) and diethyl bromomalonate (134 mg, 0.56 mmol) under Ar. After being stirred at room temperature for 6.5 h, the reaction mixture was hydrolyzed with 5 drops of 2 N H$_2$SO$_4$. The solution was dried over MgSO$_4$ and concentrated in vacuo. The reaction mixture was chromatographed on silica gel (1:1 toluene/hexane and then toluene). After evaporation of the solvent, 224 mg (68%) of the monoadduct C$_{61}$(CO$_2$-Et)$_2$ was obtained as a black solid. ESI-MS (KOAc/toluene/MeOH): *m/z* 1318 [M + X + K$^+$, X = C(Ph)Ph-18-crown-6].[16] ^{1}H NMR (200 Hz, CDCl$_3$/CS$_2$): δ 4.57 (q, *J* = 7.1 Hz, 4H), 1.49 (t, *J* = 7.1 Hz, 6H).

Preparation of C$_{62}$(CO$_2$Et)$_4$. Bisadducts C$_{62}$(CO$_2$Et)$_4$ were synthesized from the monoadduct C$_{61}$(CO$_2$Et)$_2$ using the same experimental conditions as those described for the preparation of the monoadduct C$_{61}$(CO$_2$Et)$_2$.[6] Flash chromatography on silica gel (eluent: toluene and then 1000:1 toluene/EtOAc) was used for preliminary product separation. After removal of the starting material, several other fractions were separated. The bisadduct structures were assigned by comparison of the order of elution, the yields, and UV/vis spectra with those reported by Hirsch.[6b] The first fraction contained isomers **8** and **7** while the second fraction is a mixture of isomers **6**, **5**, and **4**. The third fraction is pure isomer **3**, and the last fraction includes isomer **2** as well as trisadducts.

A semipreparative Econosil Silica HPLC column was used to isolate seven bisadducts, isomers **8**, **7**, **6**, **5**, **4**, **3**, and **2**, in a ratio of 2.1:12:31:9.3:37:6.0:2.5. The eluent was 20% hexane in toluene for isomers **8** and **7**, toluene for the mixture of isomers **6**, **5**, and **4**, and 0.6% EtOAc in toluene for isomer **2**. HPLC analysis of the original reaction mixture also indicated essentially the same ratio of these bisadducts (eluent: toluene and then 0.6% EtOAc in toluene; Figure 1). Isomers **8** and **2** were not obtained in sufficient quantities and purity for spectral analysis. Spectral data for the other five bisadducts are as follows: **Isomer 7**. ESI-MS (KOAc/toluene/MeOH): *m/z* 1476 [M + X + K$^+$, X as above]. ^{1}H NMR: δ 4.69 (q, *J* = 7.1 Hz, 4H), 4.52 (q, *J* = 7.1 Hz, 4H), 1.61 (t, *J* = 7.1 Hz, 6H), 1.48 (t, *J* = 7.1 Hz, 6H). **Isomer 6**. ESI-MS (KOAc/toluene/MeOH): *m/z* 1476 [M + X + K$^+$, X as above]. ^{1}H NMR: δ 4.56 (q, *J* = 7.1 Hz, 4H), 4.46 (q, *J* = 7.1 Hz, 4H), 1.52 (t, *J* = 7.1 Hz, 6H), 1.44 (t, *J* = 7.1 Hz, 6H). **Isomer 5**. ESI-MS (KOAc/toluene/MeOH): *m/z* 1476 [M + X + K$^+$, X as above]. ^{1}H NMR: δ 4.53 (q, *J* = 7.1 Hz, 4H), 4.46 (q, *J* = 7.1 Hz, 4H), 1.50 (t, *J* = 7.1 Hz, 6H), 1.43 (t, *J* = 7.1 Hz, 6H). **Isomer 4**. ESI-MS (KOAc/toluene/MeOH): *m/z* 1476 [M + X + K$^+$, X as above]. ^{1}H NMR: δ 4.49, 4.46, 4.43 (3q, *J* = 7.1 Hz, 8H), 1.48, 1.46, 1.42 (3t, *J* = 7.1 Hz, 12H). **Isomer 3**. ESI-MS (KOAc/toluene/MeOH): *m/z* 1476 [M + X + K$^+$, X as above]. ^{1}H NMR: δ 4.48 (q, *J* = 7.1 Hz, 4H), 4.42 (q, *J* = 7.1 Hz, 4H), 1.46 (t, *J* = 7.1 Hz, 6H), 1.40 (t, *J* = 7.1 Hz, 6H).

Preparation of ^{3}He@C$_{62}$(CO$_2$Et)$_4$. To a solution of ^{3}He@C$_{60}$ (80 mg, 0.11 mmol) in 150 mL of toluene were added NaH (53 mg, 2.2 mmol) and diethyl bromomalonate (86 mg, 0.33 mmol) under argon. The solution was stirred at room temperature for 2 h. The reaction mixture was hydrolyzed with 2 N H$_2$SO$_4$, washed with water, dried over MgSO$_4$, and concentrated to give 150 mg of black-brown solid. No other separation or purification of the reaction mixture was done prior to HPLC and ^{3}He NMR analysis of the mixture (Figure 2). The five major bisadducts, isomers **7**, **6**, **5**, **4**, and **3**, were separated using the same experimental conditions as described above in the preparation of C$_{62}$(CO$_2$Et)$_4$ without ^{3}He. The same experimental procedure was used to prepare a mixture of bisadduct **4** (equatorial) and the **4**−**4** (eq, eq, eq) trisadduct ^{3}He@C$_{63}$(CO$_2$Et)$_6$ from **4**−^{3}He@C$_{62}$(CO$_2$Et)$_4$. ^{3}He NMR (500 MHz, 4:1 1-methylnaphthalene/CD$_2$Cl$_2$): (isomer **7**) δ −9.14; (isomer **6**) δ −9.68; (isomer **5**) δ −8.89; (isomer **4**) δ −9.84; (isomer **3**) δ −10.2; (**4**−**4** trisadduct) δ −11.9.

Preparation of (*N*-Methylpyrrolidino)-C$_{60}$.[14] A mixture of C$_{60}$ (110 mg, 0.15 mmol), *N*-methylglycine (27 mg, 0.30 mmol), and paraformaldehyde (23 mg, 0.75 mmol) was heated at reflux in 200 mL of toluene under Ar for 2 h. The resulting brown solution was washed with water, dried over Na$_2$SO$_4$ and concentrated in vacuo. The crude product was purified by flash chromatography on silica gel (eluent: toluene and then 100:1 toluene/triethylamine), affording 52 mg (45%) of the monoadduct. ESI-MS (TFA/toluene/MeOH): *m/z* 778 (M + H$^+$); ^{1}H NMR (CDCl$_3$/CS$_2$): δ 4.42 (s, 4H), 3.02 (s, 3H).

Preparation of Bis(*N*-methylpyrrolidino)-C$_{60}$.[17] *N*-methylpyrrolidine bisadducts of C$_{60}$ were synthesized from (*N*-methylpyrrolidino)-C$_{60}$ using the same experimental conditions as those described for the preparation of the monoadduct. Flash chromatography on silica gel (eluent: 100:1 toluene/triethylamine and then 100:5:1 toluene/ethyl acetate/triethylamine) was used for preliminary product separation. The first fraction contains bisadducts **8**, **7**, **6**, and **4**. The second fraction contains bisadducts **5** and **3**, as well as trisadducts. A semipreparative Econosil Silica HPLC column was used to isolate bisadducts **8**, **7**, **6**, **5**, **4**, and **3** in a ratio of 7.3:20:18:24:5.6:25 [eluent: 1000:1:1 toluene/ethyl acetate/triethylamine for isomers **8**, **7**, **6**, and **4**; 1000:1:1 toluene/MeOH/triethylamine for isomers **5** and **3** (see Figure 2)]. Four pure isomeric bisadducts were obtained in sufficient quantities for spectral analysis. **Isomer 7**. ESI-MS (TFA/toluene/MeOH): *m/z* 835 [M + H$^+$]; ^{1}H NMR: δ 4.64 (d, *J* = 9.3 Hz, 2H), 4.46 (d, *J* = 9.3 Hz, 2H), 4.32 (d, *J* = 6.6 Hz, 2H), 4.30 (d, *J* = 6.6 Hz, 2H), 3.05 (s, 6H). **Isomer 6**. ESI-MS (TFA/toluene/MeOH): *m/z* 835 [M + H$^+$]; ^{1}H NMR: δ 4.41 (d, *J* = 9.6 Hz, 2H), 4.32 (d, *J* = 9.6 Hz, 2H), 4.16 (d, *J* = 9.4 Hz, 2H), 4.06 (d, *J* = 9.4 Hz, 2H), 2.92 (s, 6H). **Isomer 5**. ESI-MS (TFA/toluene/MeOH): *m/z* 835 [M + H$^+$]; ^{1}H NMR: δ 4.30 (d, *J* = 10.0 Hz, 2H), 4.16 (d, *J* = 10.0 Hz, 2H), 4.06 (d, *J* = 9.6 Hz, 2H), 4.03 (d, *J* = 9.6 Hz, 2H), 2.88 (s, 6H); ^{13}C NMR (500 MHz, CDC$_{13}$/CS$_2$): δ 154.38 (2C), 152.45 (2C), 151.24 (2C), 150.75 (2C), 150.48 (2C), 149.51 (1C), 149.08 (2C), 148.19 (2C), 147.77 (2C), 147.27 (2C), 146.12 (2C), 145.98 (4C), 145.47 (2C), 145.83 (2C), 145.81 (2C), 144.51 (2C), 142.53 (2C), 142.03 (2C), 141.67 (2C), 141.65 (2C), 141.30 (2C), 141.16 (2C), 139.07 (2C), 138.53 (2C), 136.01 (2C), 135.33 (2C), 131.16 (1C), 128.91 (1C), 128.15 (1C), 70.05 (2 CH$_2$), 69.81 (2C), 69.58 (2C), 69.39 (2 CH$_2$), 41.38 (CH$_3$). **Isomer 3**. ESI-MS (TFA/toluene/MeOH): *m/z* 835 [M + H$^+$]; ^{1}H NMR: δ 4.05 (d, *J* = 8.6 Hz, 2H), 4.03 (d, *J* = 8.6 Hz, 2H), 3.98 (d, *J* = 8.6 Hz, 2H), 3.88 (d, *J* = 8.6 Hz, 2H), 2.80 (s, 6H).

Preparation of *N*-Methylpyrrolidine Bisadducts of ^{3}He@C$_{60}$. A mixture of 50 mg (0.069 mmol) of ^{3}He@C$_{60}$, 19 mg (0.213 mmol) of *N*-methylglycine, and 10 mg (0.333 mmol) of paraformaldehyde was heated at reflux in 150 mL of toluene under argon for 2 h. The resulting brown solution was washed with water, dried over sodium sulfate, and concentrated in vacuo. No further purification was done before HPLC analysis. For ^{3}He NMR, unreacted ^{3}He@C$_{60}$ and the monoadduct were first separated by flash chromatography on silica gel (eluent: 100:1 toluene/triethylamine), and the mixture of bis- and trisadducts in the second fraction was analyzed by ^{3}He NMR (Figure 3). The major bisadducts, isomers **7**, **6**, **5**, and **3**, were separated using the same experimental conditions as described above for the C$_{60}$ bisadducts without ^{3}He. ^{3}He NMR (500 MHz, 1-methylnaphthalene/CD$_2$Cl$_2$): (isomer **7**) δ −10.93; (isomer **6**) δ −12.36; (isomer **5**) δ −10.14; (isomer **3**) δ −12.33.

Preparation of ^{3}He@C$_{60}$H$_2$ and ^{3}He@C$_{60}$H$_4$. To a solution of ^{3}He@C$_{60}$ (85%, with 15% ^{3}He@C$_{70}$, 30 mg, 0.035 mmol) in 30 mL of toluene was added a 1 M solution of borane in THF (164 mL, 164 mmol) at 0 °C under nitrogen. The reaction mixture was stirred at 0 °C for 1.5 h. HPLC (Buckyclutcher I, 1:1 toluene/hexane) showed 7% conversion. The reaction was quenched by addition of water. The toluene layer was washed once with water, and then concentrated to a small volume and passed through a SiO$_2$ flash column (1:5 toluene/hexane) to give 17 mg of a mixture of ^{3}He@C$_{60}$ and ^{3}He@C$_{60}$H$_2$ (~17% product by HPLC). ^{3}He NMR (500 MHz, 1-methylnaphthalene/CD$_2$-Cl$_2$): δ −6.34 (^{3}He@C$_{60}$), −9.66 (^{3}He@C$_{60}$H$_2$), −28.78 (^{3}He@C$_{70}$).

Bisaddition to C$_{60}$

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This material was then reduced further using either diborane or diimide[20] to give a mixture containing ^{3}He@C$_{60}$H$_4$. ^{3}He NMR (500 MHz, 1-methylnaphthalene/CD$_2$Cl$_2$): δ −6.34 (^{3}He@C$_{60}$), −9.66 (^{3}He@C$_{60}$H$_2$), −10.30, −10.81, −11.26, −11.56, −12.75, −12.79 (^{3}He@C$_{60}$H$_4$), −28.78 (^{3}He@C$_{70}$) (see Figure 4).

Supporting Information Available: ^{3}He NMR spectra (Figures 5−14) of purified bisadducts from Hirsch and Prato reactions on ^{3}He@C$_{60}$ and a closeup view of the region between −10.0 and −13.0 ppm for the mixture of isomers of ^{3}He@C$_{60}$H$_4$ from diimide reduction of ^{3}He@C$_{60}$ (10 pages). See any current masthead page for ordering and Internet acess instructions.

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