Pergamon

Tetrahedron Letters 41 (2000) 9839–9842

TETRAHEDRON
LETTERS

Diels–Alder reaction of [60]fullerene with cyclooctatetraene and electrophilic addition to the cycloadduct

Hiroshi Ishida,[a] Kenichi Komori,[a] Kenji Itoh[a,]* and Masatomi Ohno[b,]*

[a]*Department of Molecular Design and Engineering, Graduate School of Engineering, Nagoya University, Chikusa, Nagoya 464-8603, Japan*

[b]*Department of Materials Science and Engineering, Toyota Technological Institute, 2-12-1 Hisakata, Tempaku, Nagoya 468-8511, Japan*

Received 28 July 2000; revised 30 August 2000; accepted 22 September 2000

Abstract

[60]Fullerene reacted with cyclooctatetraene as a dienic partner in the Diels–Alder reaction to give the 1:1 cycloadduct in satisfactory yield (51%), which was attained by heating at relatively low temperature (110°C) and for an extended period (2 days). The cycloadduct underwent electrophilic addition reactions in a manner somewhat different from the usual reactions.

Keywords: [60]fullerene; Diels–Alder reaction; cyclooctatetraene; electrophilic addition reaction; self-sensitized photo-oxygenation.

Functionalization of [60]fullerene has been extensively studied because of interest in materials science and pharmacological applications.[1] The cycloaddition methodology is an effective approach to this functionalization, and successful reactions have been exemplified through a variety of cycloadditions on the [60]fullerene surface.[2] Among them, the Diels–Alder reaction is demonstrated to be a useful tool for introduction of representative functionalities (e.g. hydroxy, amino, nitro, carboxyl, formyl, and cyano groups and so on).[3] This reaction is also applicable for preparation of doubly functionalized derivatives of [60]fullerene including diol, diketone, and dicarboxylic acid.[4] In this respect, cyclooctatetraene (**1**) is intriguing as a dienic partner since it can bring two kinds of olefinic functions into the corresponding tricyclic cycloadduct. The reaction of these olefins on cyclobutene and bicyclooctene rings is significant under electrophilic conditions, which are compatible with the opposite nature of a fullerene core. Such differences in reactivity promises functional conversion of the double bonds with various electrophiles selectively on the addend. From these standpoints, we have undertaken the Diels–Alder reaction

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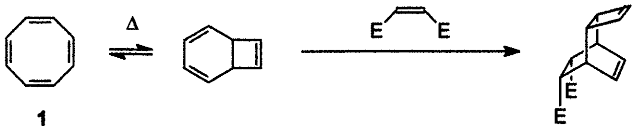
* Corresponding authors. Tel: +81-52-809-1889; fax: +81-52-809-1721; e-mail: ohno@toyota-ti.ac.jp

0040-4039/00/$ - see front matter
PII: S0040-4039(00)01689-0

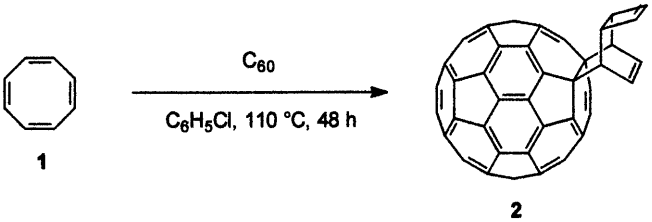
of [60]fullerene with **1** and some typical electrophilic addition reactions of the resulting cycloadduct, showing the unique feature of [60]fullerene.

The pioneering work by Reppe disclosed that **1** has enough reactivity with usual electron-deficient olefins to afford cyclobutene-fused bicyclo[2.2.2]octenes with high stereoselectivity (Scheme 1).[5]



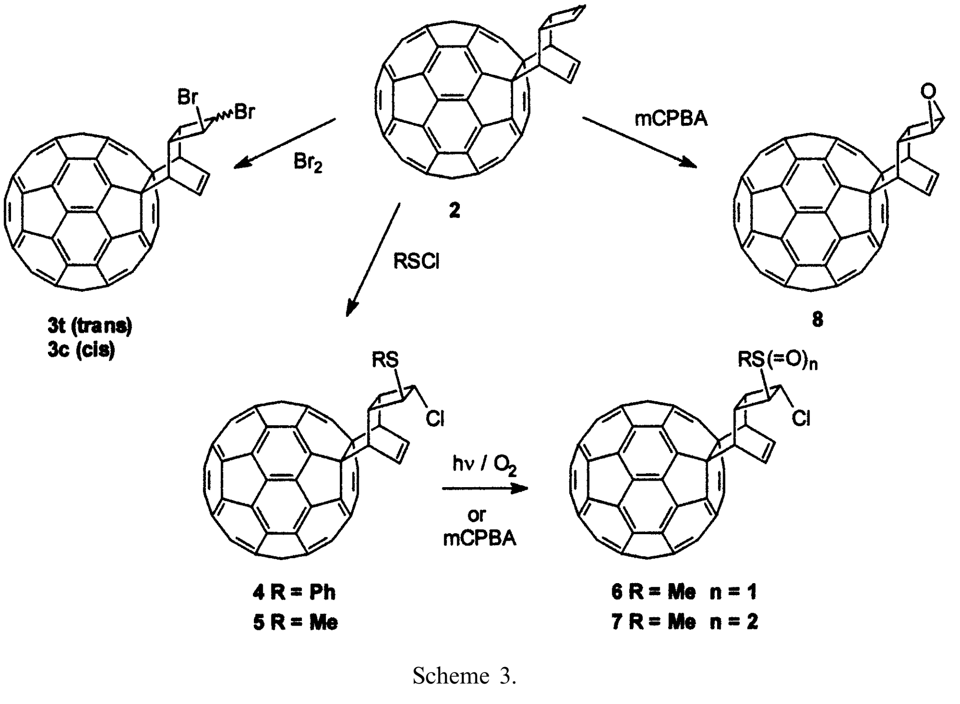
Scheme 1.

This mode of reaction is naturally adequate for [60]fullerene which is demonstrated to have the same Diels–Alder reactivity as *N*-phenylmaleimide.[6] Thus, the cycloaddition of C_{60} with **1** was conducted under thermal conditions. First, the reaction temperature around 150°C, typical for general dienophiles,[5] was employed. While the stoichiometric reaction at 150°C in *o*-dichlorobenzene was sluggish, the use of 5 equiv. of **1** gave the expected 1:1 cycloadduct **2** in 34% yield (76% yield based on consumed C_{60}). However, the excess use of **1** (10 equiv.) increased the formation of multiadducts, and higher temperature (180°C) shortened the reaction time but lowered the yield to 28%. The results of prolonged heating at this temperature were much less satisfactory, giving only trace amounts of the product as a result of retro Diels–Alder reaction. These tendencies prompted us to carry out the reaction with moderately excessive reagent at relatively low temperature for extended reaction time. Thus, the yield reached 51% (79% yield based on consumed C_{60}) by heating with 5 equiv. of **1** at 110°C for 48 h (Scheme 2). The product was separable with HPLC (Buckyprep column eluted with toluene), and the structure was elucidated as expected, 9,10-[60]fullerotricyclo-[4.2.2.0^{2,5}]deca-3,7-diene, by spectral data. FAB MS showed the 1:1 cycloadduct structure by the expected molecular ion peak at *m*/*z* 824 together with the base peak at 720. This was supported by the IR absorption at 527 cm^{-1}, characteristic of 6,6-cycloadduct of C_{60}. C_s-symmetry of the product with a tricyclic addend was confirmed by both ^{1}H and ^{13}C NMR spectra (500 MHz and 125 Hz, respectively, in $CDCl_3/CS_2$ 1:1). In the ^{1}H NMR spectra, reasonable signals due to two bridgeheaded methine protons at δ 4.19 (m) and 4.26 (m), and two olefinic protons at δ 6.27 (m) and 6.93 (m) were observed. In the ^{13}C NMR spectra, signals at δ 46.36 and 49.10 (*sp*^{3}-C) and 131.34 and 138.46 (*sp*^{2}-C) due to an attached tricyclic ring and at δ 69.73 (6.6 *sp*^{3}-C) and 136.17–155.57 (31 lines,[7] *sp*^{2}-C) due to the fullerene core were compatible with the assigned C_s-symmetric structure.



Scheme 2.

Although some Diels–Alder cycloadducts of C_{60} tend to undergo cycloreversion,[3] the cycloadduct **2** remained intact after storage for 3 months. This stability allows the further derivatization of **2**. Double bonds on the addend are essentially susceptible to electrophilic reaction, and this property is advantageous for the selective addition to occur on these bonds rather than on the fullerene double bonds which favor nucleophilic reactions. Some electrophilic reactions of the Diels–Alder cycloadducts of **1** are documented to involve transannular π-participation between the two double bonds in spatial proximity; typically, bromine was reported to add instantly in this fashion to give cross and *cis* addition products.[8] When **2** was allowed to react with equivalent amounts of bromine at ambient temperature, relatively slow addition (2.5 h) occurred to give *trans*- and *cis*-isomers **3t** and **3c** in 45 and 52% yields, respectively, after HPLC separation. The weak π-participation reflected in the products may be explained by a fullerenyl-substituent effect. Electron-availability of the π-bond of bicyclooctene is possibly reduced by the electron-accepting nature of fullerene. From a steric viewpoint, trapping of a π-participated carbocation from the backside is apparently impeded by the fullerene surface. In the case of sulfur electrophiles, the reaction is believed to proceed via a episulfonium intermediate which leads to the *trans* addition.[8c] This manner was operative also in the reaction of **2**, but the characteristics of fullerene were observed in the product. Whereas benzenesulfenyl chloride reacted with **2** in chlorobenzene at room temperature for 2 h to give a normal adduct **4**, the reaction of methanesulfenyl chloride was accompanied with self-sensitized photooxygenation to give a sulfoxide derivative **6** in 41% yield, together with a sulfide derivative **5** (58%) after treatment for 6 h. The sulfoxide **6** was obtained in 83% yield after prolonged reaction time (17 h). This result is apparently attributed to the ability of the fullerene adduct to produce singlet oxygen[9] which can oxidize sulfides.[10] While related sulfide derivatives (dihydrothiophene- and benzothiochroman-fused C_{60}) resisted such photooxygenation partly because of a steric effect,[11] the present case indicates that a sulfide within a fullerene-based molecule is automatically



Scheme 3.

oxidized to the corresponding sulfoxide if it is located at a remote position and is sufficiently nucleophilic. Alternatively, a sulfone derivative **7** was obtained by oxidation with *m*-chloroperbenzoic acid in chlorobenzene at room temperature for 2 h. This oxidant was utilized for epoxidation of **2** under similar conditions (72 h) to give **8** in 40% yield (Scheme 3).

In summary, [60]fullerene was functionalized by Diels–Alder reaction with cyclooctatetraene (**1**) appropriately by heating at relatively low temperature for an extended period. The cycloadduct **2** was found to undergo electrophilic addition in a manner somewhat different from those of the usual cycloadducts of **1** due to the intrinsic nature of fullerene. In this paper, only the reaction of a cyclobutene double bond was scrutinized, but the bis-olefinic functionality in **2** is believed to have synthetic utility. Some scission reactions involving this and other double bonds seem to be useful for the preparation of tetrafunctionalized cyclohexane derivatives; for example, ozonolysis is a way to cyclohexanetetracarboxylic acid with all *cis*-configurations. Another interest is intramolecular [2+2] photocycloaddition for the formation of a bishomocubyl system (a possible precursor for cubane synthesis). Our future work is aimed at these reactions.

Acknowledgements

This work was financially supported by Grant-in-Aid for Scientific Research on Priority Areas (A) (No. 10146101) and Scientific Research (C) (No. 12650839).

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