Preparation of Fullerodendrimers by the Use of a Diels-Alder Reaction

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Water-soluble fullerodendrimer was obtained by the use of a Diels-Alder reaction of C_{60} with a newly designed anthryl dendrimer under an extremely mild condition in 70% yield. It is notable that this system is quite useful for the synthesis of fullerodendrimer as well as the container of fullerene. Photoexcited state of a water-soluble fullerodendrimer capable to use as a singlet oxygen sensitizer was also elucidated.
Key words: fullerodendrimer, fullerene, dendrimer, Diels-Alder reaction, anthracene

1. INTRODUCTION

Fullerene-based derivatives have been attracting a great interest in the field of structural and synthetic organic chemistry.[1] In particular, there is an increasing focus on developing applications for fullerene-functionalized dendrimers, fullerodendrimers, because of a variety of interesting features in supramolecular chemistry and material science.[2] However, the chemistry of dendrimer containing a C_{60} core had been very much limited, because only a few efficient reactions in construction of fullerodendrimer were reported.[1b,2-6] The elegant and pioneering studies reported by Fréchet,[3] Hirsch,[4] Diederich[1b] and Nierengarten[1b,5] are not so easy to be performed by almost chemist. Although a number of synthetic techniques have been devised, the [4+2] cycloaddition reactions was proved to be one of the most outstanding and expeditious methods for the functionalization of [60]fullerene to afford selectively the adducts on 6,6-ring junctions.[1a,7] In this regard, several examples of reactions of C_{60} with anthracene have been described.[8-10] However, the formation of fullerodendrimers by the use of a Diels-Alder reaction of C_{60} with anthracene derivatives had never been described untill we reported.[11,12] Recently, we have described the synthesis, characterization and photodimerization of a poly(amidoamine) dendron having an anthracene moiety at the focal point.[13] During our studies on the reactivities of the anthracene bearing the dendritic substituent, we found that this molecule underwent the reversible Diels-Alder reaction with C_{60}. A fullerodendrimer composed of poly(amidoamine) building blocks is quite rare. This paper describes the facile synthesis and characterization of a poly(amidoamine) dendron having C_{60} at the focal point. This fullerodendrimer also represents a new class of water-soluble fullerene and acts as photosensitizer to generate singlet oxygen in water.

2. EXPERIMENTAL

Anthryl dendrimers **1a** and **1b** were prepared as described before.[11,12] Synthesis of the fullerodendrimer **2a** was shown in Scheme 1. A mixture of C_{60} (56 mg, 0.08 mM) and dendron **1a** (133 mg, 0.08 mM) in 15 ml of *o*-dichlorobenzene was irradiated with a high-pressure mercury lamp ($\lambda > 300$ nm) at room temperature under a nitrogen atmosphere for 1 h. The initial purple color of the solution, due to unreacted C_{60}, became red as the reaction proceeded. After evaporation under reduced pressure below 60°C, the products were separated by HPLC (LC 918, Japan Analytical Industry, Co. Lid.) by the use of gel permeation columns (Jaigel 2H + 1H) and chloroform as eluent, to give 29 mg (21%) of the fullerodendrimer **2a** as brown oil; selected data for **2a**: ^{1}H NMR (toluene-d_8) δ 2.17 - 2.63 (m, 24H), 2.32 - 2.83 (m, 46H), 3.29 - 3.40 (m, 14H), 3.43 (d, $J = 1.6$ Hz, 2H), 3.48 (s, 24H), 3.48 - 3.57 (m, 8H), 6.91 - 7.95 (m, 9H); ^{13}C NMR (CDCl$_3$) δ 32.7, 33.8, 34.0, 36.1, 37.1, 37.5, 49.2, 49.9, 51.65, 51.67, 52.2, 52.6, 52.9, 55.0, 59.0, 65.9, 74.7, 75.6, 123.7, 125.2, 126.8, 127.8, 128.4, 129.2, 136.5, 137.3, 138.8, 140.1, 141.39, 141.4, 141.6, 141.9, 142.0, 142.1, 142.59, 142.60, 142.62, 142.64, 142.9, 144.5, 144.6, 145.0, 145.18, 145.22, 145.33, 145.37, 145.40, 145.9, 146.1, 146.2, 146.4, 146.5, 152.4, 155.8, 159.52, 159.59, 172.2, 172.4, 173.1; LD-TOF-MS for $C_{141}H_{127}N_{15}O_{24}$: m/z calcd, 2414.62 [M$^+$]; found, 2414.22.

Preparatin of fullerodendrimer **2b** was shown in Scheme 2. A mixture of C_{60} (30 mg, 0.04 mM) and dendrimer **1b** (126 mg, 0.08 mM) in 3 ml of *o*-dichlorobenzene was stirred at 45°C for 4 days under a nitrogen atmosphere. The initial purple color of the solution, due to unreacted C_{60}, became red as the reaction proceeded. After evaporation under reduced pressure below 60°C, the residue was separated by HPLC (LC 918, Japan Analytical Industry, Co. Ltd.) by the use of two gel permeation columns (Jaigel 2H + 1H) and chloroform as eluent, to afford 64 mg of the fullerodendrimer **2b** as brown oil in 70% yield; selected data for **2b**: ^{1}H NMR (CDCl$_3$) δ 2.25 (t, $J = 6.0$ Hz, 8H), 2.32 - 2.36 (m, 27H), 2.46 (t, $J = 6.0$ Hz, 10H), 2.60 - 2.68 (m, 28H), 2.72 - 2.79 (m, 6H), 3.12 - 3.21 (m, 12H), 3.59 (s, 24H), 5.79 (s, 1H), 5.83 (s, 1H), 6.95 - 6.97 (m, 2H), 7.38 - 7.43 (m, 2H), 7.69 - 7.72 (m, 2H), 7.75 - 7.77 (m, 1H), 8.04 - 8.06 (m, 2H), 8.40 (s, 1H); ^{13}C NMR (CDCl$_3$) δ 14.1, 22.6, 29.3, 30.1, 30.3, 31.9, 32.6,

37.2, 49.2, 50.0, 51.7, 52.8, 58.0, 58.1, 72.3, 72.4, 125.5, 125.5, 125.9, 126.0, 126.1, 126.7, 127.5, 127.5, 129.6, 129.7, 130.0, 133.2, 136.8, 136.9, 136.9, 137.0, 139.8, 139.9, 141.3, 141.3, 141.6, 141.6, 141.7, 142.0, 142.0, 142.0, 142.2, 142.2, 142.3, 142.3, 142.5, 142.9, 142.9, 143.1, 143.1, 144.6, 144.6, 144.6, 144.7, 145.1, 145.2, 145.3, 145.3, 145.4, 145.4, 146.1, 146.2, 146.4, 146.4, 147.5, 147.5, 147.6, 147.6, 155.2, 155.3, 167.5, 170.8, 172.3, 173.0; LD-TOF-MS for $C_{139}H_{124}N_{14}O_{23}$: m/z calcd, 2357.55 [M]; found, 2356.73..

3. RESULTS AND DISCUSSION

Fullerodendrimer **2a** was synthesized by the use of a Diels-Alder reaction in 21% (photoirradiation) and 12% (heating) yield, respectively (Scheme 1). It is notable that fullerodendrimer **2a** was easily soluble in methanol, hence the unreacted C_{60} was easily removed by filtration after the reaction. The fullerodendrimer **2a** remained stable for several weeks when stored in a freezer (-10°C).
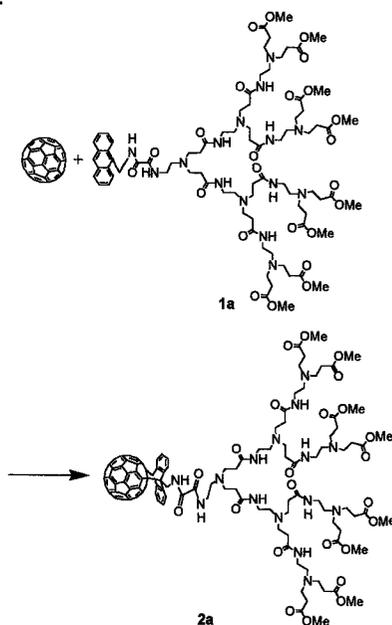
Scheme 1. A Diels-Alder reaction of C_{60} with anthryl dendrimer **1a**.

The structure of **2a** was confirmed by means of ^1H and ^{13}C NMR, UV-vis, and laser desorption ionization time-of-flight (LD-TOF) mass spectroscopic analyses. The proton signals due to the anthracene moiety of **1a** in CDCl₃ at δ 7.42 (t, 2H), 7.50 (t, 2H), 7.96 (d, 2H), 8.22 (d, 2H), 8.41 (s, 1H) disappeared. The new multiplet peaks appeared at 6.91 - 7.95 ppm suggests the formation of the fullerodendrimer **2a**. A methylene proton signal [δ 5.44 (d, J = 5.6 Hz, 2H)] of anthracene's 9-position of **1a** in toluene-d₈ disappeared and a new peak appeared at δ 3.43 (d, J = 1.6 Hz, 2H) in toluene-d₈. These assignments are rationalized by the similarity of the chemical shifts of **2a** to those of an anthracene mono-adduct of C_{60} reported by Wang et al.[9] Since the resonances characteristics of neutral anthracene protons were not observed in the NMR spectrum, this material is confirmed as a cleanly isolated adduct, not just a mixture of C_{60} and anthracene.

Figure 1 shows the ^{13}C NMR spectrum of fullerodendrimer **2a**. The fullerodendrimer **2a** has 36 resonances in the sp² region of ^{13}C NMR spectra, which indicate that the product has a C_s symmetry and that cycloaddition occurs at the 6,6-ring junction as for anthracene adduct of C_{60} reported so far.[8-10] The chemical shifts of **2a** at δ 59.0, 65.8, 74.9, and 75.8 are reasonably assigned to the bridging sp³ carbons. The former two signals are due to the bridgehead carbons of the anthracene moiety.[10] The latter two signals are ascribable to the quaternary bridgehead carbons of the C_{60} moiety.
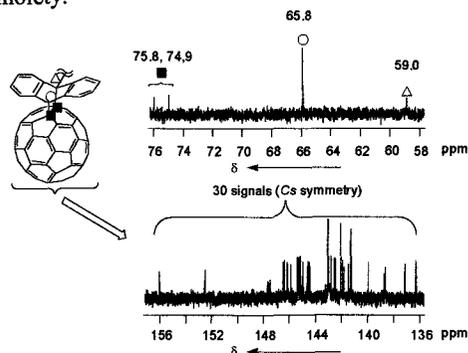

Figure 1. ^{13}C NMR spectrum of fullerodendrimer **2a**.

The UV-vis spectrum of **2a** in toluene exhibited absorptions at 434 and 702 nm, in which the 434 nm band is known to be a typical absorption in the 1:1 adduct on the 6,6-ring junction[9] as shown in Figure 2. The LD-TOF mass spectrum of **2a** by the use of negative-ion mode showed a molecular ion peak at m/z 2414.22 (**2a**, $C_{141}H_{127}N_{15}O_{24}$ requires m/z 2414.62).
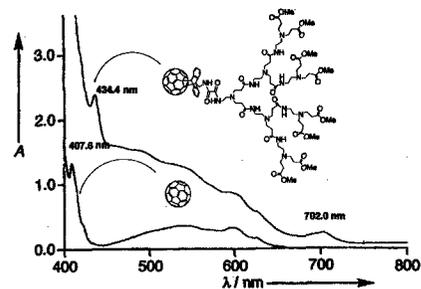

Figure 2. UV-vis spectrum of fullerodendrimer **2a** and prestine C_{60}.

Furthermore, during our studies on the reactivity of the anthryl dendrimers with C_{60}, we found that the yield was dramatically improved by changing the substituent on the anthracene moiety. In order to improve on the yield of fullerodendrimer which can be obtained by a Diels-Alder reaction, we refine upon the molecular design of anthryl dendrimer. First, a bulky dendritic substituent was moved from 9-position to 2-position, since such a huge substituent at a bridge head of [4+2]cycloadduct arisen from 9-substituted anthracene derivatives might not be preferred. Second, we used an electron-withdrawing group as a tether between an anthracene and a dendron wedge, because the cycloadducts of C_{60} with electron-deficient dienes were found to be quite stable.[14] This newly designed anthryl

dendrimer **1b** was allowed to react with C$_{60}$ to give fullerodendrimer **2b** in 70% yield (Scheme 2). This unexpected efficient formation of fullerodendrimer **2b** is more than five times as high as the yield of a Diels-Alder reaction of dendron **1a**,[11] which is the same generation as **1b**. It is notable that fullerodendrimer **2b** easily dissolves into methanol, hence the unreacted C$_{60}$ was easily removed by filtration after the reaction. The fullerodendrimer **2b** remains quite stable for several months when stored in a dark at room temperature.
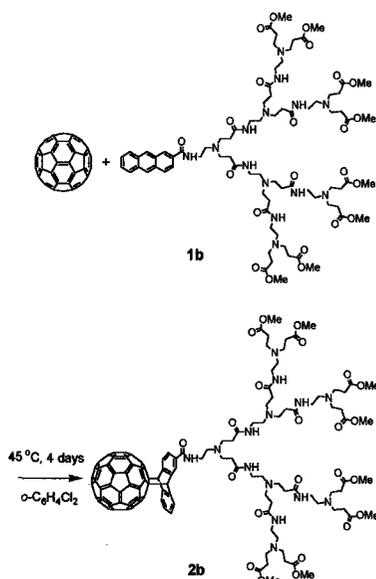
Scheme 2. Facile synthesis of fullerodendrimer **2b** by the use of a Diels-Alder reaction.

The structure of **2b** were confirmed by means of ^{1}H and ^{13}C NMR, UV-VIS, and LD-TOF mass spectroscopic analyses. The anthracene proton signals [δ 7.45 – 7.49 (m, 2H), 7.99 – 8.01 (m, 4H), 8.42 (s, 1H), 8.56 (s, 1H), 8.73 (s, 1H)] of **2b** in CDCl$_3$ disappeared and new singlet peaks of methine protons appeared at 5.79 and 5.83 ppm, respectively, and aromatic protons [δ 7.38 – 7.43 (m, 2H), 7.69 – 7.72 (m, 2H), 8.04 – 8.06 (m, 2H), 8.40 (s, 1H)] were observed (Figure 3). This result consists with the formation of fullerodendrimer **2b**, of which C$_{60}$ was connected at anthracene's 9- and 10-positions.
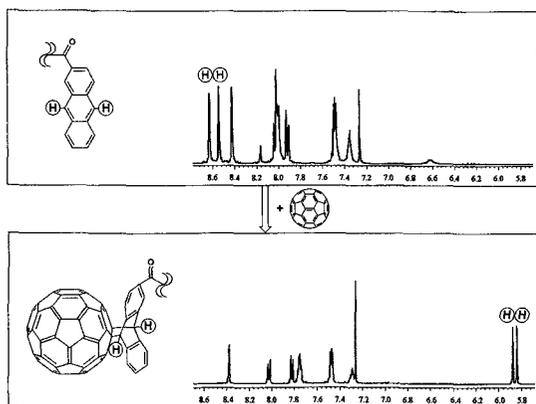

Figure 3. ^{1}H NMR spectra of anthryl dendrimer

1b (top) and fullerodendrimer **2b** (bottom).

The ^{13}C NMR spectrum of fullerodendrimer **2b** shows 55 resonances in the sp^2 region, which indicate that the product has C$_1$ symmetry. The chemical shifts of **2b** at δ = 58.0, 58.1, 72.3, and 72.4 are reasonably assigned to the bridging sp^3 carbons (Figure 4).
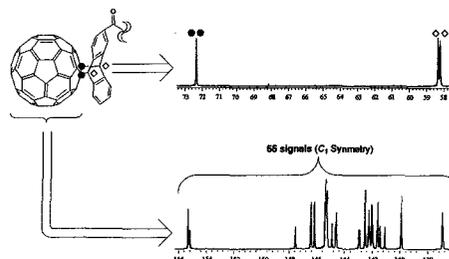

Figure 4. ^{13}C NMR spectrum of fullerodendrimer **2b**.

Figure 5 shows the UV-vis spectrum of **2b** in toluene exhibited absorptions at 433 and 704 nm, in which the former band is known to be a characteristic absorption band in the 1:1 adduct on the 6,6-ring junction[6] as for anthracene adduct of C$_{60}$ reported so far.[8-11] The LD-TOF mass spectrum of **2b** by the use of negative-ion mode without matrix showed a molecular ion peak at m/z 2356.73 (**2b**, C$_{139}$H$_{124}$N$_{14}$O$_{23}$ requires m/z 2357.55).
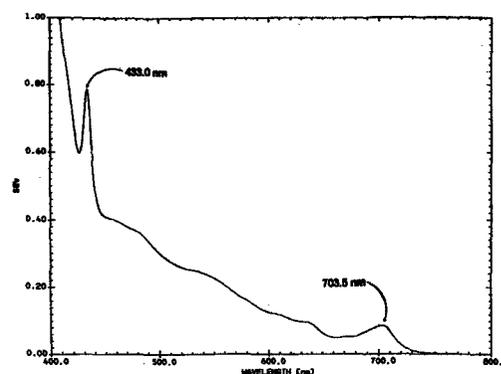

Figure 5. UV-vis spectrum of fullerodendrimer **2b**.

In order to compare the redox behavior of fullerodendrimers **2a** and **2b**, their reduction potentials in V vs Ag/AgNO$_3$ were measured by the use of cyclic voltammetry in 1,2-dichlorobenzene with Bu$_4$NPF$_6$ (0.1 M) as a supporting electrolyte. The reduction potential (E_{red}^1 = -1.12 V) of fullerodendrimer **2b** was similar to pristine C$_{60}$. In contrast to **2b**, the fullerodendrimer **2a** has more negative reduction potential (E_{red}^1 = -1.25 V) than C$_{60}$ (E_{red}^1 = -1.12 V) by 0.13 V.[11]

It is notable that the fullerodendrimer **2a** and **2b** are readily soluble in acidic water (pH = 4.0). In order to clarify the utility of a water-soluble fullerene derivative, we investigated photophysical and photochemical properties of **2a** in water. The transient spectra observed by the laser excitation of **2a** in deaerated water exhibited the absorption peak at 700 nm, which is assigned to the absorption of the triplet excited state of **2a**, because the absorption peak is in good agreement with the triplet-triplet absorption of the C$_{60}$-adducts.[15] From the decay at 700 nm, the triplet lifetime was evaluated to be

56 µs. On addition of O_2, the decay rate increased, indicating that energy transfer from the triplet state of **2a** to O_2 takes place, producing singlet oxygen. From the decay in O_2 saturated water, the rate constant for energy transfer from the triplet state of **2a** to O_2 was evaluated to be 1.3×10^9 mol^{-1} dm^3 s^{-1}. The formation of singlet oxygen was confirmed by the observation of its emission at 1280 nm in D_2O, from which the quantum yield of singlet oxygen was estimated to be 0.45 after correcting the low O_2 concentration in D_2O compared with that in toluene used as a standard.[16]

It is well-known that an adduct of C_{60} and anthracene undergoes a retro-Diels-Alder reaction easily. In order to clarify the utility of anthracenyl dendrimers **1a** and **1b** as a container of fullerene, we investigated the possibility of the retro-reaction. Heating of fullerodendrimer **2a** in methanol at 45°C for 12 h gave the component molecules, C_{60} and dendron **1a**, in 89 and 100% yields, respectively. These finding surely reveal that the reaction is reversible; i.e., there is equilibrium between bond formation and dissociation reactions, which indicate that anthryl dendrimer **1a** is useful for the host molecule for [60]fullerene. On the other hand, fullerodendrimer **2b** is more stable than **2a**. It takes 9 days to obtain the component molecules under the same reaction conditions.

4. CONCLUSION

The results described herein show a facile and efficient route to the fullerodendrimer by the use of a Diels-Alder reaction of C_{60} and anthryl dendron. So far most of the constructions of fullerodendrimer were accomplished by means of a Hirsch-Bingel reaction, which needs CBr_4 and DBU as mediator. On the contrary, our approach, which is highly convergent without any reagent, highlights a useful preparation of fullerodendrimer under convenient reaction conditions. The present work might constitute a general method for rapid synthesis of a number of fullerodendrimers. It is notable that this system is quite useful for the synthesis of fullerodendrimer as well as the container of fullerene. Photoexcited state of a water-soluble fullerodendrimer capable to use as a singlet oxygen sensitizer was also elucidated. Further work is in progress to explore the applications and advantages of the reversible formation of fullerodendrimer.

REFERENCES

[1] (a) "Fullerenes and Related Structures" Ed. by A. Hirsch, *Top. Curr. Chem.*, **199**, 1-235 (1999); (b) J. F. Nierengarten, T. Habicher, R. Kessinger, F. Cardullo, F. Diederich, V. Gramlich, J. P. Gisselbrecht, C. Boudon, and M. Gross, *Helv. Chem. Acta*, **80**, 2238 (1997); (c) F. Diederich, and C. Thilgen, *Science*, **271**, 317 (1996).

[2] A. Hirsch, and O. Vostrowsky, *Top. Curr. Chem.*, **217**, 51 (2001) and references therein.

[3] (a) K. L. Wooley, C. J. Hawker, J. M. J. Frechet, F.

Wudl, G. Srdanov, S. Shi, C. Li, and M. Cao, *J. Am. Chem. Soc.*, **115**, 9836 (1993); (b) C. J. Hawker, K. L. Wooley, and J. M. J. Frechet, *J. Chem. Soc., Chem. Commun.*, 925 (1994).

[4] (a) X. Camps, H. Schöuberger, and A. Hirsch, *Chem. Eur. J.*, **3**, 561 (1997); (b) M. Brethreich, and A. Hirsch, *Tetrahedron Lett.*, **39**, 2731 (1998).

[5] Y. Rio, J.-F. Nicoud, J.-L. Rehspringer, and J.-F. Nierengarten, *Tetrahedron Lett.*, **41**, 10207 (2000).

[6] (a) Y. Murata, M. Ito, and K. Komatsu, *J. Material Chem.*, **12**, 2009 (2002); (b) V. J. Catalano, N. Parodi, *Inorg. Chem.*, **36**, 537 (1997).

[7] For recent reviews, see: (a) "The Chemistry of Fullerenes", Ed. by R. Taylor, World Scientific, London, (1995). (b) "Fullerenes: Chemistry, Physics and Technology", Ed. by K. M. Kadish, and R. S. Ruoff, John Wiley and Sons, New York (2000).

[8] (a) Y. Murata, N. Kato, K. Fujiwara, and K. Komatsu, *J. Org. Chem.*, **64**, 3483 (1999); (b) K. Mikami, S. Matsumoto, T. Tonoi, Y. Okubo, T. Suenobu, and S. Fukuzumi, *Tetrahedron Lett.*, **39**, 3733 (1998); (c) P. Curz, A. Hoz, F. Langa, B. Illescas, and N. Martín, *Tetrahedron*, **53**, 2599 (1997); (d) B. Kräutler, T. Müller, J. Maynollo, K. Gruber, C. Kratky, P. Ochsenbein, D. Schwarzenbach, and H.-B. Bürgi, *Angew. Chem., Int. Ed.*, **35**, 1204 (1996); e) K. Komatsu, Y. Murata, N. Sugita, K. Takeuchi, and T. S. M. Wan, *Tetrahedron Lett.*, **34**, 8473 (1993).

[9] J. A. Schlueter, J. M. Seaman, S. Taha, H. Cohen, K. R. Lykke, H. H. Wang, and J. M. Williams, *Chem. Commun.*, 972 (1993).

[10] M. Tsuda, T. Ishida, T. Nogami, S. Kurono, and M. Ohashi, *Chem. Commun.*, 1296 (1993).

[11] Y. Takaguchi, T. Tajima, K. Ohta, J. Motoyoshiya, H. Aoyama, T. Wakahara, T. Akasaka, M. Fujitsuka, and O. Ito, *Angew. Chem. Int. Ed.*, **41**, 817 (2002).

[12] Y. Takaguchi, Y. Sako, Y. Yanagimoto, S. Tsuboi, J. Motoyoshiya, H. Aoyama, T. Wakahara, and T. Akasaka, *Tetrahedron Lett.*, **44**, 5777 (2003).

[13] Y. Takaguchi, T. Tajima, K. Ohta, J. Motoyoshiya, H. Aoyama, *Chem. Lett.*, 1388 (2000).

[14] (a) A. Mori, Y. Takamori, and H. Takeshita, *Chem. Lett.*, 395 (1997); (b) H. Takeshita, J.-F. Liu, N. Kato, A. Mori, and R. Isobe, *J. Chem. Soc., Perkin Trans. 1*, 1433 (1994); (c) M. Ohno, T. Azuma, S. Kojima, Y. Shirakawa, and S. Eguchi, *Tetrahedron*, **52**, 4983 (1996); (d) K.-F. Liou, T.-Y. Hsiao, and C.-H. Cheng, *Fullerene Sci. Technol.*, **6**, 351 (1998); (e) M. Ohno, Y. Shirakawa, and S. Eguchi, *Synthesis*, 1812 (1998); (f) S. Mori, T. Karita, K. Komatsu, N. Sugita, and T. S. M. Wan, *Synth. Commun.*, **27**, 1475 (1997); (g) C.-F. Yen, R. K. Peddinti, and C.-C. Liao, *Org. Lett.*, **18**, 2909 (2000).

[15] C. Luo, M. Fujitsuka, A. Watanabe, O. Ito, L. Gan, Y. Hung, and C.-H. Hung, *J. Chem. Soc. Faraday Trans.*, **94**, 527 (1998).

[16] J. W. Arbogast, and C. S. Foote, *J. Am. Chem. Soc.*, **113**, 8886 (1991).