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Facile and reversible synthesis of an acidic water-soluble poly(amidoamine) fullerodendrimer

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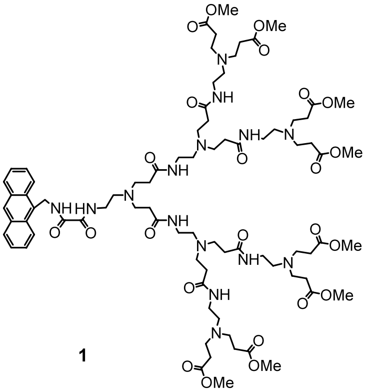
Abstract—Water-soluble fullerodendrimer was obtained by the use of a Diels–Alder reaction of C_{60} with a newly designed anthryl dendron under an extremely mild condition in 70% yield, which is more than five times as high as the yield described in our previous report.

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. Recently, we have described the reversible formation of fullerodendrimers by the use of a Diels–Alder reaction of C_{60} with anthryl dendron (**1**).[7] During our studies on the reactivity of the anthracene derivatives with C_{60}, we found that the yield was dramatically improved by changing the substituent on the anthracene moiety. This paper describes the facile preparation and characterization of a water-soluble poly(amidoamine) fullerodendrimer (**2**).

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 anthracenyl dendron **1** which was employed in a previous paper.[7] First, a bulky dendritic substituent was moved from 9-position to 2-position, since it might not be preferred at a bridge head of [4+2]cycloadduct arisen from 9-substituted anthracene derivatives.



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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.[8] This newly designed anthryl dendron (**3**) was actually prepared according to our strategy previously reported (Scheme 1).[9]

A focal point of dendron, compound (**4**), was obtained by reaction of 2-anthracenecarboxylic acid methyl ester (**5**) with ethylenediamine. Subsequently, treatment of **4** with methyl acrylate produced a dendron (**3a**) in 85% yield. This two-step process can be repeated to prepare (**3b**) and (**3c**) in 85 and 50% yields, respectively. The structures of **3a**, **3b**, and **3c** were confirmed by ^1H, ^{13}C

Keywords: fullerodendrimer; anthracene; cycloaddition; water-soluble fullerene.

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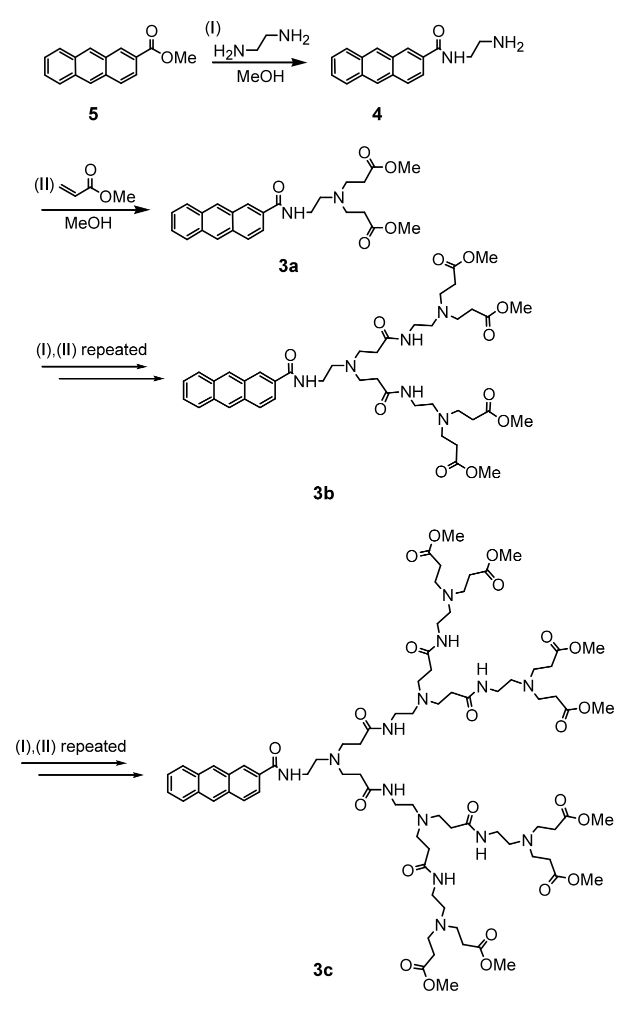
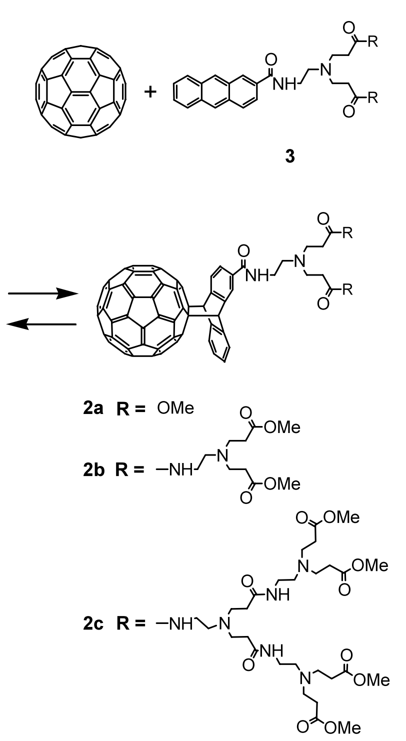


Scheme 1. Synthesis of anthryl dendrons **3a**–**c**.

NMR spectroscopies, elemental analysis, and MALDI-TOF MS.[10]

The preparation of fullerodendrimer **2** was carried out as shown in Scheme 2. In a typical run, a mixture of C_{60} (30 mg, 0.04 mM) and dendron **3c** (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 (**2c**) as brown oil in 70% yield. This unexpected efficient formation of fullerodendrimer **2c** is more than five times as high as the yield of a Diels–Alder reaction of dendron **1**,[7] which is the same generation as **3c**. Furthermore, and to our knowledge, this is the highest yield of the reaction of C_{60} with anthracene derivatives. It is notable that fullerodendrimer **2c** easily dissolves into methanol, hence the unreacted C_{60} was easily removed by filtration after the reaction. The fullerodendrimer **2c** remains quite stable for several months when stored in the dark at room temperature.



Scheme 2. Preparation of fullerodendrimer **2a**–**c**.

The structures of **2a**–**c** were confirmed by means of ^{1}H and ^{13}C NMR, UV–vis, and LD-TOF mass spectroscopic analyses.[11] 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 **3c** 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. This result consists with the formation of fullerodendrimer **2c**, of which C_{60} was connected at anthracene's 9- and 10-positions. The ^{13}C NMR spectrum of fullerodendrimer **2c** shows 55 resonances in the sp^2 region, which indicate that the product has C_1 symmetry. The chemical shifts of **2c** at $\delta = 58.0$, 58.1, 72.3, and 72.4 are reasonably assigned to the bridging sp^3 carbons. The UV–vis spectrum of **2c** 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.[7,12–14] The LD-TOF mass spectrum of **2c** by the use of negative-ion mode without matrix showed a molecular ion peak at m/z 2356.73 (**2c**, $C_{139}H_{124}N_{14}O_{23}$ requires m/z 2357.55) (Fig. 1). In order to compare the redox behavior of fullerodendrimers prepared from **1** and **2**, their reduction potentials in V versus ferrocene/ferrocenium (Fc/Fc^+) were measured by the use of cyclic voltammetry in 1,2-dichlorobenzene with Bu_4NBF_4 (0.05 M) as a supporting electrolyte. The reduction potential ($E^1_{red} = -1.12$ V) of fullerodendrimer **2c** was similar to pristine C_{60}. In contrast to **2c**, the fullerodendrimer prepared from dendron **1** has more negative reduction potential ($E^1_{red} = -1.25$ V) than C_{60} ($E^1_{red} = -1.12$ V) by 0.13 V.[7] It is notable that fullerodendrimer **2c** is readily soluble in acidic water (more than 30 mg/ml at pH 1.50).

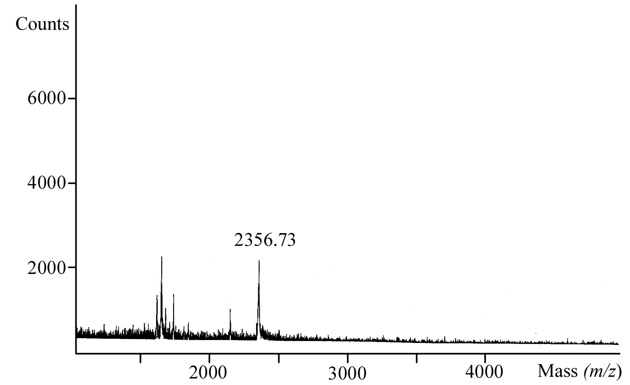


Figure 1. Negative-ion LD-TOF mass spectrum of fullerodendrimer **2c**.

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 dendron **3** as a container of fullerene, we investigated the possibility of the retro-reaction. Heating of fullerodendrimer **2c** in methanol at 45°C for 9 days gave the component molecules, C_{60} and dendron **3c**, in 89 and 91% yields, respectively. These findings surely reveal that the reaction is reversible; i.e. there is equilibrium between bond formation and dissociation reactions. It is notable that the reaction rate was lowered to 1/20 as compared with a retro-Diels–Alder reaction of fullerodendrimer made of **1** under the same condition.[15]

The results described herein show a facile and efficient route to the fullerodendrimer by the use of a newly designed 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. Further work is in progress to explore the applications and advantages of the reversible formation of fullerodendrimer.

Acknowledgements

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10. Selected data for **3a**: ^{1}H NMR ($CDCl_3$) δ 2.48 (t, $J=6.4$ Hz, 2H), 2.70 (t, $J=4.8$ Hz, 2H), 2.80 (t, $J=6.4$ Hz, 4H), 3.54 (s, 6H), 3.62–3.66 (q, $J=5.6$ Hz, 2H), 7.35 (brs, 1H), 7.48–7.50 (m, 2H), 7.91–8.05 (m, 4H), 8.43 (s, 1H), 8.63 (s, 1H). Anal. calcd for $C_{25}H_{28}N_2O_5$: C, 68.79; H, 6.47; N, 6.42. Found: C, 68.45; H, 6.58, N, 6.34. For **3b**: ^{1}H NMR ($CDCl_3$) δ 2.43 (t, $J=6.8$ Hz, 8H), 2.49 (t, $J=5.6$ Hz, 4H), 2.54 (t, $J=5.6$ Hz, 4H), 2.72 (t, $J=6.8$ Hz, 8H), 2.86 (t, $J=5.6$ Hz, 2H), 2.98 (t, $J=5.6$ Hz, 4H), 3.30–3.35 (q, $J=5.6$ Hz, 4H), 3.73 (s, 12H), 3.79–3.83 (q, $J=5.6$ Hz, 2H), 6.98 (t, $J=5.2$ Hz, 2H), 7.59–7.62 (m, 2H), 7.49–8.04 (m, 5H), 8.42 (s, 1H), 8.55 (s, 1H), 8.72 (s, 1H); ^{13}C NMR ($CDCl_3$) δ 32.4, 33.7, 36.9, 37.5, 48.9, 49.2, 51.4, 52.6, 123.4, 125.5, 125.8, 125.9, 127.8, 127.9, 128.0, 128.1, 128.4, 130.5, 131.2, 131.7, 131.9, 132.4, 167.1, 172.2, 172.8; MALDI-TOF-MS for $C_{43}H_{60}N_6O_{11}$: m/z calcd, 836.97 [MH$^+$]; found, 837.83. For **3c**: ^{1}H NMR ($CDCl_3$) δ 2.29(t, $J=6.4$ Hz, 8H), 2.37–2.41 (m, 16H), 2.45–2.51 (m, 16H), 2.70–2.76 (m, 26H), 2.86 (t, $J=6.0$ Hz, 4H), 3.23–3.25 (m, 12H), 3.63 (s, 24H), 3.67–3.69 (q, $J=4.0$ Hz, 2H), 7.01 (t, $J=5.2$ Hz, 4H), 7.45–7.49 (m, 2H), 7.62 (t, $J=4.4$ Hz, 2H), 7.99–8.01 (m, 4H), 8.17 (t, $J=4.8$ Hz, 1H), 8.42 (s, 1H), 8.56 (s, 1H) 8.73 (s, 1H); ^{13}C NMR ($CDCl_3$) δ 32.1, 32.6, 33.8, 34.0, 37.1, 37.4, 37.8, 49.1, 49.2, 49.6, 51.5, 52.4, 52.8, 123.5, 125.6, 125.9, 126.0, 128.0, 128.1, 128.2, 128.3, 128,6, 130.7, 131.3, 131.9, 132.1, 132.5, 167.3, 172.3, 172.4, 173.0; MALDI-TOF-MS for $C_{79}H_{124}N_{14}O_{23}$: m/z calcd, 1636.90 [MH$^+$]; found, 1637.43.

11. Selected data for **2a**: ^{1}H NMR (CDCl$_3$) δ 2.46 (t, $J=6.0$ Hz, 4H), 2.69 (t, $J=6.0$ Hz, 2H), 2.77–2.81 (m, 4H), 3.55 (s, 6H), 3.60–3.65 (m, 2H), 5.84 (s, 1H), 5.88 (s, 1H), 7.29 (t, $J=8.0$ Hz, 1H), 7.47–7.49 (m, 2H), 7.75–7.76 (m, 2H), 7.82 (d, $J=8.0$ Hz, 1H), 8.02 (t, $J=4.0$ Hz, 1H), 8.38 (s, 1H); ^{13}C NMR (CDCl$_3$) δ 29.7, 32.7, 37.4, 48.9, 51.6, 52.8, 58.2, 58.3, 72.3, 72.3, 125.0, 125.7, 125.9, 126.0, 126.3, 127.5, 127.5, 133.6, 136.9, 136.9, 137.0, 139.9, 139.9, 141.1, 141.4, 141.6, 141.6, 142.0, 142.0, 142.0, 142.2, 142.2, 142.3, 142.5, 143.0, 143.0, 144.5, 144.6, 144.6, 144.9, 145.2, 145.2, 145.3, 145.3, 145.3, 145.4, 145.6, 146.1, 146.1, 146.2, 146.4, 146.4, 147.5, 147.5, 155.2, 155.3, 155.3, 167.0, 173.0; LD-TOF-MS for $C_{85}H_{28}N_2O_5$: *m*/*z* calcd, 1157.14, [M$^-$]; found, 1156.54. For **2b**: ^{1}H NMR (CDCl$_3$) δ 2.24–2.35 (m, 16H), 2.55 (t, $J=6.0$ Hz, 8H), 2.63–2.82 (m, 6H), 3.12 (q, $J=5.0$ Hz, 4H), 3.54–3.65 (m, 14H), 5.78 (s, 1H), 5.82 (s, 1H), 6.79 (t, $J=4.0$ Hz, 2H), 7.38–7.43 (m, 2H), 7.67–7.71 (m, 2H), 7.74 (d, $J=8.0$ Hz, 1H), 7.79–7.93 (m, 1H), 8.04 (d, $J=8.0$ Hz, 1H), 8.39 (s, 1H); ^{13}C NMR (CDCl$_3$) δ 32.7, 33.8, 37.1, 37.7, 49.1, 51.6, 52.4, 52.8, 52.8, 71.5, 71.5, 125.2, 125.5, 125.7, 125.9, 126.0, 126.2, 126.4, 126.6, 127.2, 127.4, 127.5, 128.3, 133.5, 133.7, 136.1, 139.4, 141.1, 141.3, 141.4, 141.7, 141.8, 142.0, 142.1, 142.3, 142.4, 142.4, 142.7, 142.8, 142.8, 143.5, 143.6, 143.8, 143.9, 144.0, 144.0, 144.1, 144.7, 144.8, 144.9, 145.1, 145.2, 145.3, 145.4, 145.5, 145.7, 145.7, 145.8, 146.1, 146.2, 147.1, 147.1, 147.2, 147.8, 147.8, 148.1, 148.2, 148.3, 148.5, 148.6, 149.1, 155.0; LD-TOF-MS for $C_{103}H_{60}N_6O_{11}$: *m*/*z* calcd, 1557.61 [M$^-$]; found, 1556.84. For **2c**: ^{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.
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