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Anhydride-functionalized fullerene: a versatile precursor for fullerene-based materials

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ABSTRACT

Soluble phthalic anhydride-functionalized fullerene was generated via simple pyrolysis of the corresponding di-*t*-butyl phthalate precursor at 200 °C for 120 min. This non-chemical method for generating electrophilic fullerene may be advantageous for the preparation of various fullerene-containing materials. The utility of the resulting fullerene anhydride was demonstrated by solution coupling reaction with PEG-amine, surface reaction with amine-functionalized glass, and hydrolysis reaction to form amphiphilic fullerene.

Fullerenes have found many promising applications in the areas of material science and nanotechnology due to their unique electronic and physical properties.[1] To utilize these properties, the chemical conjugation of fullerenes with materials of interest is desirable, and many fullerene modification methodologies have been developed. Some representative examples include nucleophilic addition, carbene addition, [4+2] or [3+2] cycloaddition, azide addition, and zwitterion addition.[1a,2] These protocols allow the conjugation of fullerenes to various materials, such as dyes, polymers, nanoparticles, and biomolecules. However, when the substrate to be conjugated is more precious than fullerenes, or more sensitive to the reaction conditions, the formation of a direct covalent bond to fullerenes by the above-mentioned protocols may suffer from low yields and/or require sophisticated reaction conditions. Recently, 'click-chemistry' (Huisgen [3+2] cycloaddition reaction) has proved to be a powerful tool for preparation of various fullerene-based hybrid materials under mild and selective conditions.[3] However, this method also requires the pre-installation of either alkyne or azide functionality to the counterpart materials for the coupling, which costs additional synthetic steps. In this respect, the development of a '*ready-to-react*' fullerene derivative that can react with a conventional functional group already present in a substrate by simple mixing and without any co-reagent requirement is highly desirable. Since amine groups are ubiquitous functional groups found in many synthetic and natural molecules, we envisioned that fullerenes possessing an anhydride group could be a useful precursor for fullerene-conjugated materials. Although there have been a few reports on the preparation of anhydride-functionalized [60]fullerenes, the resulting fullerenes were not suitable for further reaction due to their insolubility in common solvents.[4] Here, we report an easy and practical approach to the preparation of a soluble anhydride-functionalized [60]fullerene that can react with various amine-containing materials. Since anhydride groups are sensitive to conventional purification techniques such as silica gel-based chromatography, we employed the pyrolysis of di-*t*-butyl phthalate to generate anhydride functionality, which requires no further purification.

The desired di-*t*-butyl phthalate **4** was prepared in three steps, starting with commercially available di-*t*-butyl acetylene dicarboxylate (**1**) and myrcene (**2**) and following the modified procedure of Hoye and co-workers.[5] We chose the Prato reaction for derivatizing fullerene because the physicochemical properties of fullerene are known to be preserved in the resulting fulleropyrrolidine derivatives.[6] The Prato reaction between aldehyde **3** and C_{60} fullerene in the presence of sarcosine in refluxing toluene resulted in the desired di-*t*-butyl phthalate-functionalized fullerene **4** at a relatively high yield (44%, Scheme 1).[7] The resulting di-*t*-butyl phthalate **4** was highly soluble in common organic solvents, and the structure was verified by ^{1}H and ^{13}C NMR, FT-IR spectroscopy, and ESI-HRMS. [^{1}H NMR (500 MHz, $CDCl_3$) δ 1.57 and 1.58 (*t*-butyl), 3.02 (NCH_3), 3.98 (CH_3NCHCH_2), 4.19 ($CH_3NCH_aH_b$), 4.85 ($CH_3NCH_aH_b$), 7.32, 7.47, and 7.61 (Ar-H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.26 and 28.27 (*t*-butyl), 32.37 ($ArCH_2$), 33.07 ($ArCH_2CH_2$), 40.28 (NCH_3), 70.38, 70.50, 76.27 and 77.30 (two sp^{3} fullerene carbons and CH_2NCH), 81.88 and 82.17 (two $C(CH_3)_3$ carbons), 128.84–156.50 (56 signals from C_{60} and aryl group), 166.64 and 167.35 (ester carbonyl); IR (KBr) 1719 cm^{-1}

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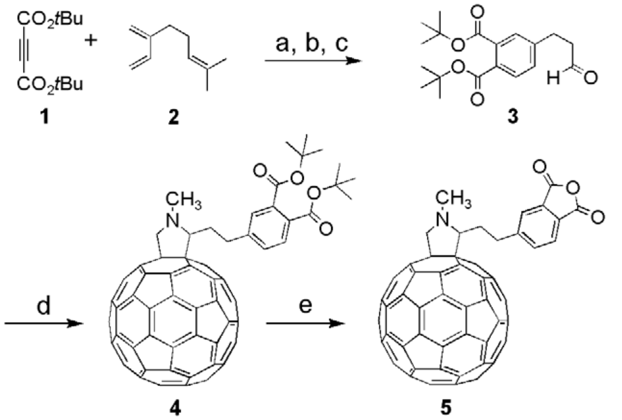


Scheme 1. Reagents and conditions: (a) toluene, 110 °C, 6 h, 89%; (b) DDQ, 85 °C, 1 h, 96%; (c) O_3/DMS, 70%; (d) sarcosine, C_{60}, toluene, reflux, 6 h, 44%; (e) 200 °C, 2 h, >99%.

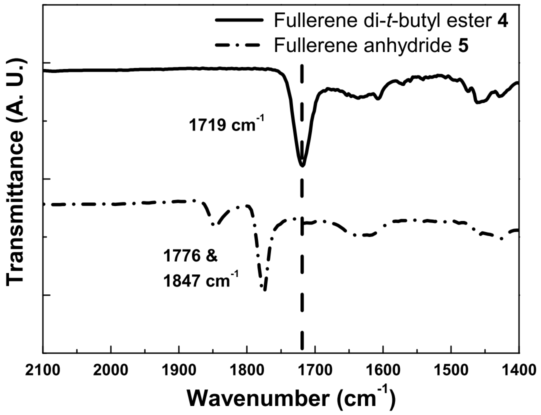


Figure 2. IR spectra of **4** and **5**.

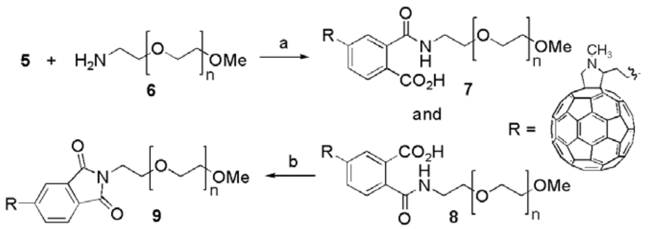
(ester); ESI-HRMS *m/e* calculated for $C_{81}H_{31}NNaO_4$ $[M+Na]^+$ 1104.2151, found 1104.2147].

Next, we investigated the pyrolysis of di-*t*-butyl phthalate to phthalic anhydride. Fullerene di-*t*-butyl phthalate **4** was placed in NMR tubes and heated at 200 °C, and the reaction progress was monitored by ^{1}H NMR spectroscopy (Fig. 1). The resonances for *t*-butyl groups (δ 1.57 and 1.58) and the aromatic protons of di-*t*-butyl phthalate **4** [δ 7.32 (d), 7.47 (s), and 7.61 (d)] gradually disappeared and new peaks in the aromatic region appeared at δ 7.76 (d), 7.91 (s), and 7.95 (d) which are assigned to fullerene anhydride **5**. The methylene and methine peaks in the tether shifted slightly downfield, and the intensity of *N*-methyl peak at δ 3.05 remained almost constant, which indicates that the *N*-methyl pyrrolidine group survived the pyrolysis conditions. The reaction was complete in 120 min. Fortunately, no significant retro-cycloaddition reaction of the pyrrolidinofullerene[8] moiety was observed under these conditions.[9]

FT-IR spectra of **4** and **5** also indicated complete conversion of di-*t*-butyl phthalate into phthalic anhydride. The C=O stretch for di-*t*-butyl ester at 1719 cm^{-1} shifted to two new peaks at 1776 and 1847 cm^{-1}, which are the characteristic peaks for phthalic anhydride groups (Fig. 2).[10] ESI-HRMS analysis also supported the identity of **5** by showing a relevant peak at *m/e* 952.0980 (*m/e* calculated for $C_{73}H_{14}NO_3$ $[M+H]^+$ 952.0974).

To demonstrate the use of fullerene anhydride **5**, it was reacted with methoxy polyethylene glycol amine **6** (MeO-PEG-NH_2, M_n = 5000 g/mol, M_w/M_n = 1.06, Polymer Source) in THF. After stirring for 1 h at room temperature (rt), the resulting PEG-conjugated fullerenes **7** and **8** were purified by simple precipitation in diethyl ether (Scheme 2).

^{1}H NMR analysis of the product indicated that the terminal amine group of **6** was fully transformed into two regio-isomeric amic acids **7** and **8** in a ~1:1 ratio as shown in Figure 3a-(3). The two sets of resonances for the two amic acids **7** and **8** converged



Scheme 2. Reagents and conditions: (a) THF, rt, 1 h, 89%; (b) neat, 90 °C, 19 h, 95%.

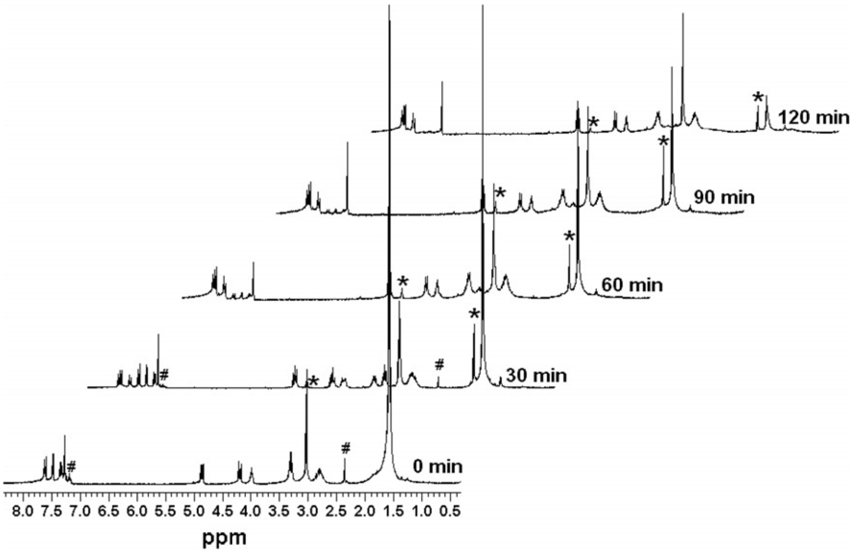


Figure 1. ^{1}H NMR monitoring of pyrolysis of **4** (*: isobutene, #: toluene).

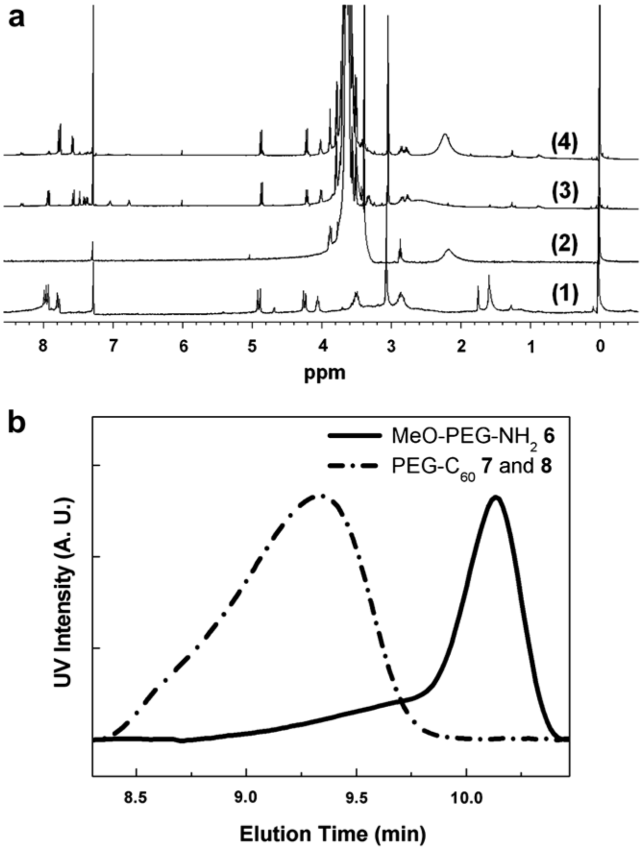


Figure 3. ^1H NMR spectra of (1) fullerene anhydride **5**, (2) MeO-PEG-NH$_2$ (**6**), (3) MeO-PEG-C$_{60}$ conjugates **7** and **8** (amic acid forms), and (4) MeO-PEG-C$_{60}$ conjugate **9** (phthalimide form), (b) UV (250 nm) detected GPC traces of MeO-PEG-NH$_2$ pretreated with phenyl isocyanate (solid line) and MeO-PEG-C$_{60}$ conjugates **7** and **8** (amic acid forms) (dash-dotted line).

to one set of resonances after heating at 90 °C for 19 h, which indicates ring closure of the amic acids into phthalimide **9** (Fig. 3a-(4)). GPC analysis also showed that the molecular weight of the PEG increased after the coupling reaction (Fig. 3b). Broadening of the GPC trace after the coupling is attributable to the aggregation behavior of the resulting fullerene-PEG, which is generally observed phenomenon for fullerene-containing polymers.[11]

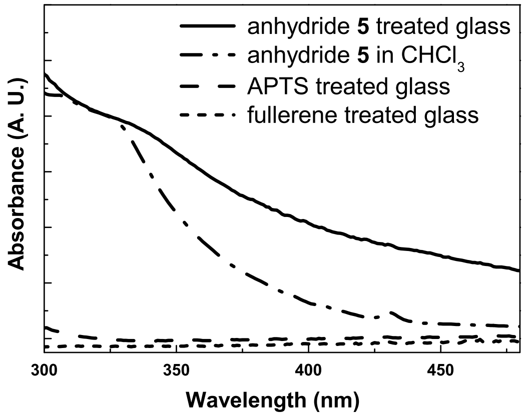
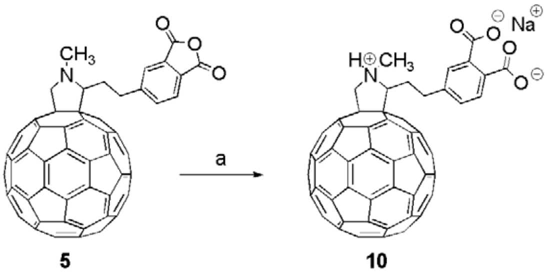


Figure 4. UV–vis spectra of a [60]fullerene-treated APTS-modified glass slide (short dashed line), an APTS-treated glass slide (dashed line), a solution of anhydride **5** (dash-dotted line, 3.1×10^{-6} M in CHCl$_3$), and anhydride **5**-treated APTS-modified glass slide (solid line).

In order to demonstrate the feasibility of fullerene anhydride **5** in a surface reaction, an amine-functionalized glass slide obtained by 3-aminopropyltriethoxysilane (APTS) treatment[12] was immersed in a CHCl$_3$ solution of **5** for 1 h at room temperature (rt) and then characterized by UV–vis spectroscopy (Fig. 4). Significantly strong absorption at ~330 nm was observed for the anhydride **5**-treated glass slide and a solution of anhydride **5**, while an APTS-treated glass slide was essentially transparent in this region. In support of this result, the fullerene anhydride **5**-treated APTS-glass substrate showed a considerable increase in the water



Scheme 3. Reagents and conditions: (a) NaOH (aq), THF, rt, overnight.

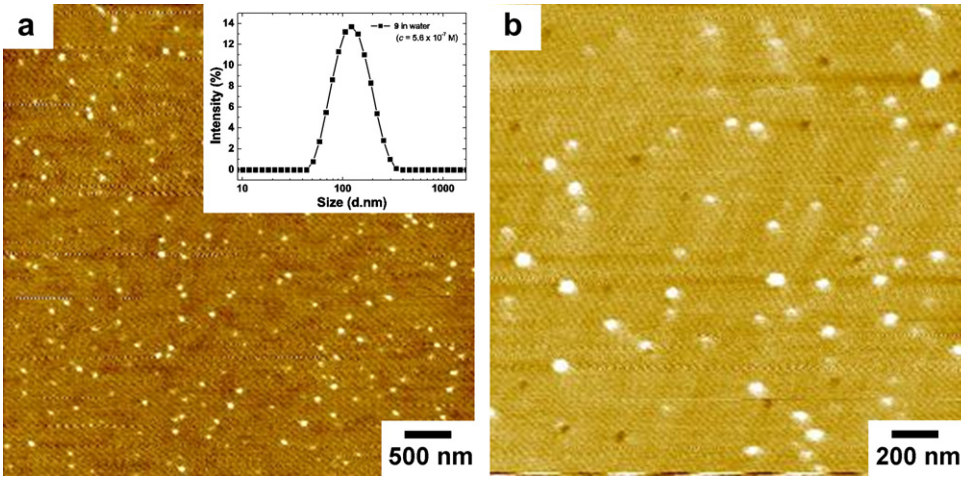


Figure 5. Atomic force microscope image (AC mode) of 5.6×10^{-7} M aqueous solution of amphiphilic fullerene derivative **10** on mica. (a) 5 × 5 μm. Inset shows hydrodynamic diameter distribution of amphiphilic fullerene derivative **10** in an aqueous solution with $c = 5.6 \times 10^{-7}$ M, (b) 2 × 2 μm.

contact angle.[12] [Piranha-treated glass (<6°), APTS-treated glass (50°), and fullerene anhydride **5**-treated APTS-glass (71°) (Fig. S5)].

Amphiphilic fullerene derivative **10** could be easily prepared from fullerene anhydride **5** by hydrolysis reaction (Scheme 3). One equivalent of aqueous NaOH solution was added to a THF solution of fullerene anhydride **5**. After stirring the two-phase mixture overnight at rt and removing THF by evaporation, deionized water was added to dissolve all precipitates. Finally, an orange-colored clear solution of **10** was obtained.

It is well known that amphiphilic fullerene derivatives tend to form self-assembled nanostructures in various shapes such as spheres, vesicles, needles, rods, and tubules.[13] Atomic force microscopy (AFM) images of a drop-cast sample of **10** on mica showed that amphiphilic fullerene **10** forms spherical aggregates in regular sizes as shown in Figure 5. Dynamic light scattering (DLS) measurement of the solution (5.6×10^{-7} M) indicated that the hydrodynamic diameter of the aggregates was 116 nm with polydispersity index of 0.240 (Fig. 5a inset).

In conclusion, we have developed an efficient way of preparing phthalic anhydride-functionalized fullerene via simple pyrolysis of a di-*t*-butyl phthalate precursor. Because this protocol can produce a high yield of the fullerene anhydride without using any additional reagents or solvents, the anhydride can be directly subjected to coupling reactions without further purification, which had previously been an obstacle to the introduction of this useful functional group on fullerenes. The resulting fullerene anhydride **5** exhibits good solubility in common organic solvents and high reactivity with various amine-containing materials. We envision that this methodology may also be applicable to the functionalization of other thermally stable solid materials with anhydride groups such as carbon nanotubes, silicates, and zeolites.

Acknowledgments

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Supplementary data

Supplementary data (experimental details and spectral characterization data for **3**–**5** and **7**–**10**) associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2008.07.064.

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