Fullerenes

DOI: 10.1002/ange.200602431

Selective Electrochemical Retro-Cycloaddition Reaction of Pyrrolidinofullerenes[**]

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Since the discovery of fullerenes, various methods for their functionalization have been developed and explored extensively.[1] Among the most widely employed derivatization reactions are Diels–Alder cycloadditions,[2] cyclopropanations,[3] and azomethine 1,3-dipolar cycloaddition reactions.[4] The cyclopropanation reaction,[3a] which forms a cyclopropano (methano) addend on the fullerene sphere, and the 1,3-

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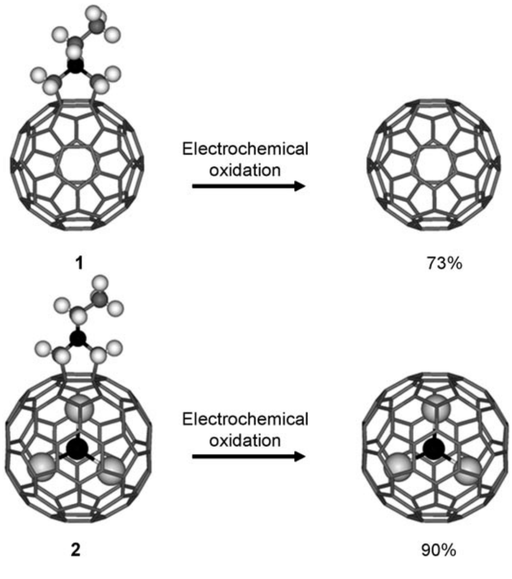
[**] This work was financially supported by the US NSF (CHE-0509989), the MEC of Spain, and Comunidad de Madrid (Projects CTQ 2005-02609/BQU, MAT-02 12196-E, and P-PPQ-000225-0505). M.A. thanks the MEC for a research grant. This material is based upon work supported by Luna Innovations Incorporated and the Air Force Office of Scientific Research under Contract No. FA9550-05-C-0146. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Air Force Office of Scientific Research.

dipolar cycloaddition reaction,[4a] which results in a pyrrolidine ring adduct, were first introduced in 1993. The products of these two reactions (methanofullerenes and pyrrolidinofullerenes) exhibit high thermal and chemical stability, whereas some Diels–Alder adducts are unstable upon heating and undergo thermal retro-cycloaddition reactions.[5] The instability of methano adducts under electrochemically reductive conditions was discovered in the late 1990s, and it has since been used as an effective method for retro-cyclopropanation reactions.[6] The di(alkoxycarbonyl)methano bridges can be efficiently removed from the carbon sphere by exhaustive controlled-potential electrolysis (CPE). This electrochemical retro-cyclopropanation reaction has been found to be of general applicability for different fullerenes and highly selective towards removal of cyclopropano addends in the presence of other types of addends.[7–8] Chemical reductive methods have also been employed for efficient retro-cyclopropanation reactions.[9]

Until recently, pyrrolidino[3,4:1,2][60]fullerenes (commonly known as fulleropyrrolidines) were believed to be the most stable adducts under various experimental conditions and were presumed not to undergo chemical, thermal, or reductive retro-cycloaddition reactions. However, some of us recently showed that the 1,3-dipolar cycloaddition reaction is thermally reversible.[10] The efficient removal of pyrrolidine rings from the various parent fullerenes occurred upon heating in the presence of a highly efficient dipolarophile.

The mechanism of the 1,3-dipolar retro-cycloaddition reaction is still not clear. Preliminary results suggested that both thermal cycloreversion and oxidative processes are possible mechanistic pathways. This latter possibility inspired us to probe the oxidative electrochemical properties of pyrrolidinofullerenes **1** and **2** further. Herein, we report the first efficient removal of pyrrolidine rings from fullerenes by electrochemical oxidation (Scheme 1).

N-Ethyl pyrrolidinofullerene **1** was synthesized according to previously established procedures for 1,3-dipolar additions.[4a] Controlled-potential electrolysis was employed for the electrochemical oxidation at an applied potential determined from cyclic-voltammetry (CV) experiments. The cyclic voltammogram of compound **1** in *o*-diclorobenzene (*o*-DCB) showed three reversible reduction waves, which correspond to the reduction of the fullerene core, and one irreversible oxidative wave (Figure 1). The irreversible wave was assigned to a pyrrolidine-based oxidation process, a strong suggestion of the instability of **1** upon electrochemical oxidation. Therefore, we electrolyzed **1** at a potential 100 mV more positive than this oxidation wave (1 V vs. the ferrocene/ferrocenium (Fc/Fc$^+$) couple). First, the electrolysis was conducted in *o*-DCB containing 0.05 M tetrabutylammonium hexafluorophosphate (TBAPF$_6$) with the exclusion of oxygen and light.[11] The electrolysis was stopped after charge corresponding to 1.8 electrons per molecule was transferred, and the solution was reduced at 0 V. The net charge that was transferred to the solution upon re-reduction corresponded to only 0.45 electrons per molecule. C$_{60}$ could not be detected by CV during the electrolysis in *o*-DCB, probably because of blocking of the electrode surface as a result of the generation of by-products. The reaction mixture was purified by column chromatography (silica gel, CS$_2$), and C$_{60}$ was obtained in 73 % yield (Scheme 1). In a different experiment, the appearance of C$_{60}$ during the course of the electrolysis in dichloromethane (DCM) could be detected directly by CV (Figure 1).



Scheme 1. Electrochemical retro-cycloaddition of *N*-ethyl pyrrolidino[3,4:1,2][60]fullerene (**1**) and *N*-ethyl pyrrolidinofullerene Sc$_3$N@C$_{80}$ (**2**).

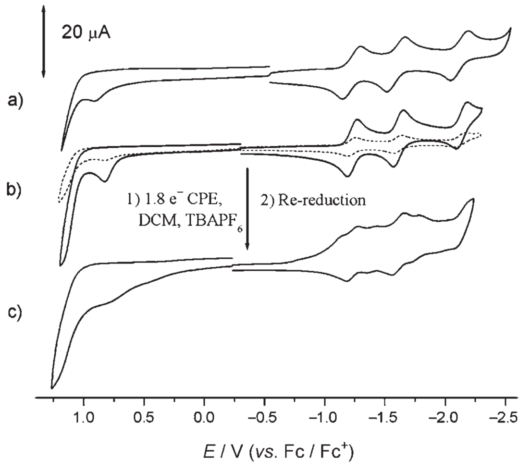


Figure 1. a) Cyclic voltammogram of **1** in 0.05 M TBAPF$_6$ *o*-DCB; scan rate 100 mV s^{-1}. b) Cyclic voltammogram of **1**, in 0.1 M TBAPF$_6$ DCM; scan rate 100 mV s^{-1}. Initially, **1** had low solubility in DCM (dotted line). Upon reductive electrolysis at the first reductive wave, and subsequent reoxidation, **1** was solubilized (solid line). c) Cyclic voltammogram after partial electrolysis of **1** in DCM.

The applicability of the electrochemical retro-cycloaddition reaction to other fullerene species was further confirmed by the oxidative electrolysis of the *N*-ethyl pyrrolidinofullerene of Sc$_3$N@C$_{80}$ (**2**; Figure 2). Compound **2** was synthesized by a previously reported procedure,[12] and its cyclic voltammogram exhibited three reversible reduction waves and three irreversible oxidative waves (Figure 2 a).[13] CPE was conducted at a potential of 0.45 V vs. Fc/Fc$^+$, which is 0.55 V lower than the potential required for the electrolysis of the C$_{60}$

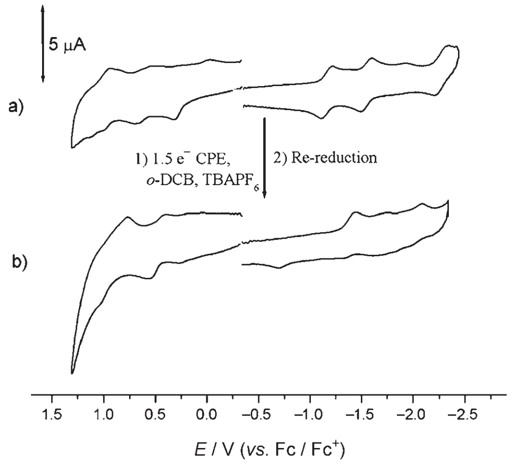
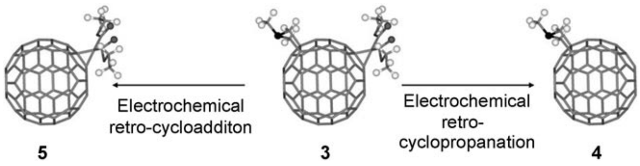


Figure 2. a) Cyclic voltammogram of **2** in 0.05 M TBAPF$_6$ *o*-DCB; scan rate 100 mV s^{-1}. b) Cyclic voltammogram after oxidative electrolysis of **2**.

derivative **1**. The voltammogram of **2** showed drastic changes after transfer of a charge corresponding to 1.5 electrons per molecule and re-reduction at zero potential. Comparison of the cyclic voltammogram of the new species in the solution with the previously reported cyclic voltammogram of $Sc_3N@C_{80}$[13] confirmed that the electrolysis was completed and the major product was $Sc_3N@C_{80}$ (90% yield, after purification by column chromatography).

The electrochemical retro-cycloaddition of compounds **1** and **2** led us to two important conclusions. First, for quantitative removal of the pyrrolidine group from the parent fullerene, the electrochemical oxidation must be performed at a potential corresponding exclusively to the oxidation of the pyrrolidine moiety but not oxidation of the fullerene cage. The higher yield obtained for the retro-cycloaddition of the *N*-ethyl pyrrolidino derivative of $Sc_3N@C_{80}$ is consistent with this finding, as the selective oxidation of the addend is more facile. Second, upon re-reduction of the electrolyzed solution at 0 V, the charge transferred corresponded to less that one electron per molecule. This observation indicated that upon completion of the electrochemical retro-cycloaddition, the parent fullerene was close to its neutral state. This result establishes a major difference from the electrochemical retro-cyclopropanation reaction, during which the fullerene species is reduced to give an anionic end state. These two findings suggest that the mechanism of the oxidative retro-cycloaddition mainly involves the pyrrolidine group with minimal involvement of the fullerene center.

To investigate the selectivity of this electrochemical oxidative retro-cycloaddition reaction, we synthesized the hybrid *e'* isomer bis adduct **3**, which contains both an *N*-methyl pyrrolidino and a bis(ethoxycarbonyl)methano addend (Scheme 2), and performed both electrolytic oxidation, to remove the pyrrolidine ring, and reduction, to remove the bis(ethoxycarbonyl)methano addend. The selective removal of the bis(ethoxycarbonyl)methano addend from a similar compound (*trans*-3 isomer) by electrochemical reduction proceeded with 63% yield.[8]



Scheme 2. Electrochemical retro-cycloaddition and retro-cyclopropanation of hybrid bis adduct **3** of C_{60}.

The reductive CPE of **3** was carried out in DCM at a potential 100 mV more negative than the second reduction peak potential (Figure 3 a, downwards arrow) and yielded *N*-methyl pyrrolidinofullerene (**4**) as a major product (89%). This result demonstrates the instability of the cyclopropane ring and the stability of the pyrrolidine addend under reductive conditions and confirms the previously reported results for the *trans*-3 isomer.[8]

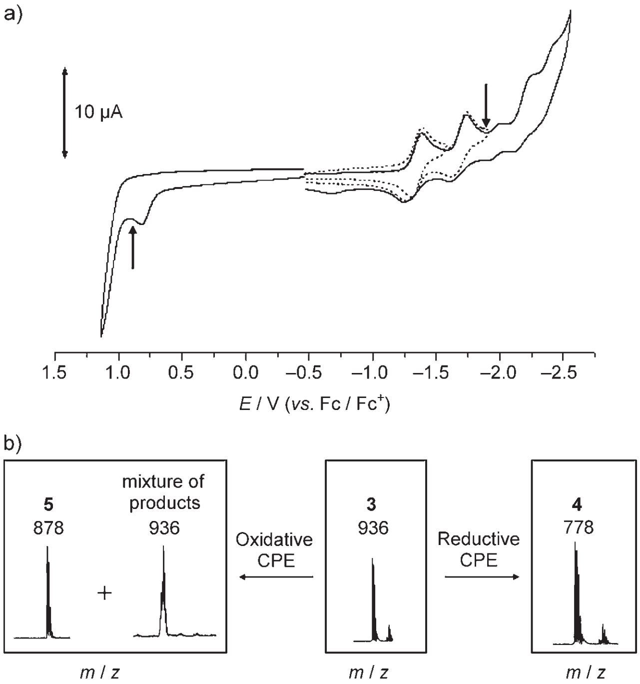


Figure 3. a) Cyclic voltammogram of **3** in 0.1 M TBAPF$_6$ in DCM; scan rate 100 mV s^{-1}. b) MALDI-TOF MS analysis of the products after electrolytic oxidation and reduction.

The oxidative CPE of **3** was performed in DCM by following the procedure established for compounds **1** and **2** (Figure 3 a, oxidation potential shown by upwards arrow). Complete characterization (TLC, MALDI-TOF MS, and ^{1}H NMR spectroscopy) of the products revealed the presence of mainly two species.

The major product (60% yield) was identified as bis(ethoxycarbonyl)methanofullerene (**5**). The other species (30% yield) consisted of a mixture of several compounds with different retention factors (TLC) from **3** but with molecular-ion peaks (MALDI-MS) corresponding to the molecular weight of **3** (Figure 3 b). We hypothesize that an isomerization reaction has occurred during electrolysis and the multiple compounds are isomeric mixed bis adducts. Most likely the pyrrolidine group has shuffled on the surface of the C_{60} sphere, in a similar manner to the previously observed "walk-on-the-sphere" rearrangement that occurs during the retro-cyclopropanation reaction.[14] This hypothesis is currently under investigation in our laboratory.

In summary, we propose electrochemical oxidative electrolysis as an alternative method to conduct thermal retro-cycloaddition reactions of fullerene derivatives. We have also shown, for the first time, the selective removal by electrochemical methods of targeted addends from a parent fullerene bearing the two most commonly used derivative groups (Scheme 2). The discovery of the retro-cyloaddition reaction creates new possibilities in protecting/deprotecting strategies for functionalization of fullerenes and also reveals the instability of the pyrrolidine addends under thermal and oxidative conditions. This latter fact represents potential difficulties for further applications of pyrrolidinofullerenes in the preparation of optoelectronic devices and should motivate the search for new, easily accessible, and more-stable functional groups.

Experimental Section

All CPE experiments were performed with a homemade cell under high vacuum with $TBAPF_6$ as supporting electrolyte, as previously described.[11]

Compounds **1**,[4a] **2**,[12] and *N*-methyl pyrrolidino[3,4:1,2][60]fullerene[4a] were synthesized according to literature procedures, and compound **3** as follows: DBU (17 μL, 0.12 mmol) was added to a solution of *N*-methyl pyrrolidino[3,4:1,2][60]fullerene[4] (50 mg, 0.06 mmol) and diethyl bromomalonate (10 μL, 0.06 mmol) in *o*-DCB. After 5 min the reaction mixture was subjected to column chromatography on silica with CH_2Cl_2. Compound **3** was isolated in 9% yield (5.5 mg). ^{1}H NMR spectroscopy (500 MHz, [D_8]toluene): $\delta = 4.06$ (q, $J = 10$ Hz, 4H), 3.68 (d, $J = 6.5$ Hz, 2H), 3.57 (d, $J = 6.5$ Hz, 2H). 2.42 ppm (s, 3H); MALDI-TOF MS (1,8,9-trihydroxyanthracene): m/z 936 [M^+].

Received: June 16, 2006

Keywords: azomethine ylides · cycloaddition · electrochemistry · fullerenes · retro reactions

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