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On the Regioselective Intramolecular Nucleophilic Addition of Thiols to C_{60}

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The first intramolecular nucleophilic addition of a thiol to a fullerene double bond is reported. Whereas the reaction of cysteine (**4**) or cystine (**11**) with formaldehyde and [60]fullerene in chlorobenzene at reflux afforded the new compound **10** bearing a thiazolidine moiety fused to the fullerene sphere, the reaction of commercially available *N*-methylglycine (**12**; sarcosine) with 1,4-dithiane-2,5-diol (**13**) and C_{60} in chlorobenzene at reflux led to the desired cyclized compound **3** in poor yield. The favorable geometrical approach of the reactive thiol group towards the fullerene double bond is followed by a 5-*exo*-*trig* intramolecular nucleophilic addition of the S–H group to the adjacent double bond of the fullerene to form compound **3** in which a tetrahydrothiophene ring is simultaneously fused to the pyrrolidine and the fullerene moieties. Compound **3** was spectroscopically and electrochemically characterized and CV revealed that saturation of a second double bond of the fullerene sphere (*cis*-1 regioisomer) is compensated by the electronegative character of the sulfur atom, resulting in reduction potentials similar to those observed for fullerene monoadducts. The two-fold cyclization reaction occurs in a totally regioselective stepwise process leading exclusively to the *cis*-1 isomer. Theoretical calculations (DFT and the ONIOM approach) predict that the formation of the sulfur pentagonal ring is highly favored and does not present structural constraints. Furthermore, the activation barrier for the nucleophilic attack of the thiol group on the fullerene surface was found to be substantially higher in comparison with the analogous previously reported hydroxy group (activation barrier about 8 kcal mol^{-1} larger for SH than for OH), thus accounting for the poor yields of tetrahydrothiophene **3**. The formation of **3** competes with the formation of 1,2-dimethylpyrrolidino[3,4:1,2][60]fullerene (**15**), which is formed as the main reaction product by loss of the SH group.

Introduction

Because of their unique spherical geometry, fullerenes constitute a singular scenario in a variety of chemical reactions in which the highly reactive double bonds (30 for the most common C_{60}) participate actively. During the last 20 years since its preparation in multigram amounts by Krätschmer et al.,[1] fullerenes have been among the most studied molecules in science. However, and surprisingly, many important reactions in the arsenal of organic chemistry have not been applied to fullerenes, despite the unprecedented chemical structures that could be formed.[2,3] Although a large number of fullerene derivatives containing sulfur atoms in the organic addend have been prepared, for example, the C_{60}-based dyads formed with the well-known electron-donating tetrathiafulvalene,[4] fullerene derivatives in which the carbon sphere is directly linked to a sulfur atom are among the less studied modified fullerenes. Eguchi and co-workers have reported the only example of a hetero-Diels–Alder reaction with C_{60}, which yields dihydrothiopyran-fused [60]fullerene derivatives through C–S bond formation on the [60]fullerene surface.[5] Nevertheless, perhaps the most frequently studied reaction is the addition of radical species to fullerenes, for example, the addition of alkylthio radicals and the photoinduced dithiolation of fullerenes with dendrimer disulfides.[6] Other sulfur-containing fullerene derivatives have also been reported, ranging from thiocarbonyl ylides and related 1,3-dipoles.[7]

Recently, we reported the synthesis of novel chemically modified fullerenes from suitably functionalized pyrrolidino[3,4:1,2][60]fullerenes[8] and, in particular, the intramolecular nucleophilic addition of the hydroxy group of a phenol[9] to a double bond of the C_{60} sphere assisted by the hydrogen bond formed between the pyrrolidine nitrogen and a second hydroxy group contained in the molecule (compound **1** in Figure 1).

The new tetrahydrofuran-fused pyrrolidino[3,4:1,2][60]-fullerene **2** has also recently been obtained by a 5-*exo*-*trig* cyclization reaction carried out in a simple one-step synthesis by nucleophilic addition of the nonisolated intermediate

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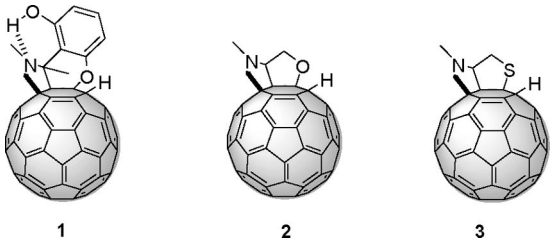


Figure 1. Chemical structures of the dihydropyran-, tetrahydrofuran- and tetrahydrothiophene-fused pyrrolidino[3,4:1,2]-[60]fullerenes (**1**, **2**, and **3**, respectively) formed by intramolecular nucleophilic addition of hydroxy (**1** and **2**) and thiol (**3**) groups to the fullerene double bond.

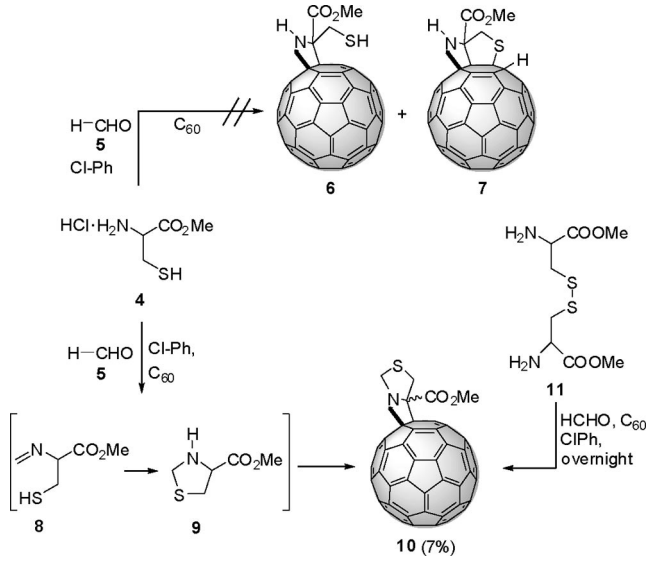
alcohol to the fullerene double bond, forming a new pentagonal ring from commercially available starting materials.[10]

Encouraged by the availability and easy access to these totally regioselectively modified fullerenes endowed with unusual fused saturated heterocyclic rings, we decided to expand the synthesis to a new family of sulfur-containing saturated heterocycles by intramolecular nucleophilic addition of a thiol group to the fullerene double bond to obtain new C_{60}-based fused tetrahydrothiophene derivatives. This new reaction on the fullerene surface has been theoretically investigated by density functional theory (DFT) using the two-layered ONIOM approach. This study reveals a favorable formation of the sulfur-containing pentagonal ring with an exothermic reaction energy. However, in agreement with experimental findings, the activation barrier for the nucleophilic attack of the thiol group on the fullerene surface has been found to be substantially higher in comparison with the analogous hydroxy group (activation barrier is around 8 kcal mol^{-1} larger for SH than for OH).

Results and Discussion

Our first chemical approach to the preparation of the new compound **3** was based on the reaction of the commercially available amino acid cysteine **4** (as the methyl ester hydrochloride) with formaldehyde and [60]fullerene in chlorobenzene at reflux. However, similarly to the previously observed reaction of the related amino acid bearing a hydroxy group (hydroxymethylglycine),[10] the reaction did not afford the expected thiomethyl-functionalized compound **6** or its cyclized derivative **7** (Scheme 1). On the contrary, compound **10** with a thiazolidine moiety fused to the fullerene sphere through a pyrrolidine ring was obtained in a low yield (7%) as the only characterizable compound, the reaction leading to extensive decomposition[11] (Scheme 1).

The formation of compound **10** can be accounted for by the condensation reaction between the amino group of the cysteine moiety and the carbonyl group of formaldehyde to yield intermediate **8**, which spontaneously cyclizes to non-isolated thiazolidine **9** bearing a methoxycarbonyl group.[12] Subsequent in situ reaction of **9** (a masked cysteine) with formaldehyde generates the required azomethine ylide,



Scheme 1. Synthesis of thiazolidine-containing fullerene **10** from cysteine **4** or cystine **11** and formaldehyde (**5**) in the presence of [60]fullerene.

which reacts as a 1,3-dipole with [60]fullerene under Prato's conditions[13] to afford the thiazolidine derivative **10** in low yield (7%; 35% yield based on consumed C_{60}).

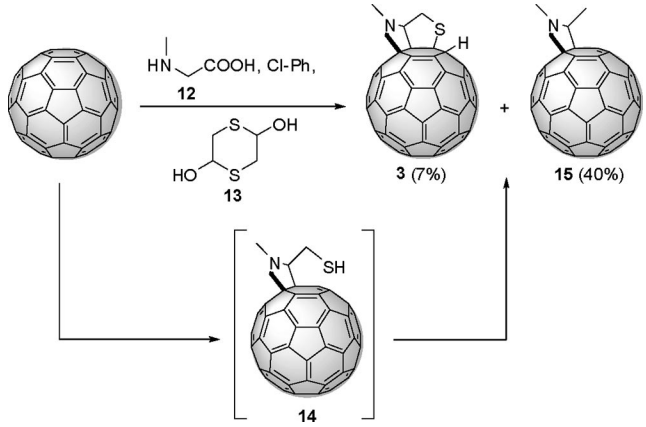
The desired compound **3** was prepared by an alternative route using cystine **11** as the starting material. Thus, treatment of cystine methyl ester bis-hydrochloride bearing a disulfide bridge should afford the expected C_{60} dimer or the compound resulting from its homolytic cleavage, which should undergo spontaneous cyclization to form **3**. However, the reaction afforded a complex mixture of compounds from which only compound **10** was obtained in 12% yield (20% yield based on consumed C_{60}).

The chemical structure of fulleropyrrolidine **10** was confirmed by spectroscopic techniques. In particular, the ^{1}H NMR spectrum shows, in addition to the presence of the methyl ester group, the presence of the methylene protons of the pyrrolidine ring, which appear as two doublets centered at δ = 4.98 and 4.75 ppm. The coupled signals at δ = 4.89 and 4.61 ppm correspond to the methylene group simultaneously attached to the sulfur and nitrogen atoms; in the HSQC analysis this methylene group, as expected, it shows coupling to the most deshielding sp^3 carbon atom at δ = 64.6 ppm due to the presence of the two electronegative heteroatoms (see Figure S3 in the Supporting Information).

Because the chemical approach using the amino ester **4** bearing the thiomethyl group leads to the undesired compound **10** in which cyclization occurs with the pyrrolidine ring instead of the fullerene double bond to form a thiazolidine ring, we turned out our attention to the use of an aldehyde endowed with a thiomethyl group as in compound **13**.

Thus, reaction of commercially available *N*-methylglycine (**12**; sarcosine) with 1,4-dithiane-2,5-diol (**13**) and C_{60} in chlorobenzene at reflux following Prato's protocol[13] afforded the desired cyclized compound **3** albeit in only 7%

yield (9% yield based on consumed C_{60}; Scheme 2). It is well known that dimer **13** undergoes thermal decomposition to form thioacetaldehyde, which, in turn, reacts with **12** and C_{60} to form intermediate **14**, which was not observed even at lower temperatures. This experimental finding is a clear indication of the favorable geometrical approach between the reactive S–H and the fullerene double bond. A favored 5-*exo*-*trig* cyclization[14] by intramolecular nucleophilic addition of the S–H group to the adjacent double bond of the fullerene leads to the formation of the unprecedented compound **3** in which a tetrahydrothiophene ring is simultaneously fused to the pyrrolidine and fullerene moieties.



Scheme 2. Synthesis of thiophene-fused pyrrolidino[3,4:1,2][60]fullerene **3** from nonisolated intermediate **14** by intramolecular nucleophilic addition of the thiol group to the fullerene double bond, together with the unexpected compound **15**.

The structure of **3** was confirmed by spectroscopic and analytical techniques. Thus, in addition to the signals corresponding to the *N*-methyl (δ =2.89 ppm) and two methylene groups (4.76 and 4.01 ppm for the CH_2–N; 3.76 and 3.72 ppm for the CH_2–S), the ^{1}H NMR spectrum of this compound showed a multiplet at δ = 4.04 ppm (N–CH–CH_2–S) and the signature typical of a hydrogen atom on the fullerene skeleton, which appears as a singlet at δ = 6.47 ppm, in good agreement with other related fullerenes bearing a hydrogen atom on the surface.[15]

To the best of our knowledge this is the first reported example of the addition of the S–H group of a neutral thiol to a double bond on the fullerene sphere, affording in a totally regioselective and site-selective manner the *cis*-1 isomer[16] in which the sulfur atom is linked to the fullerene carbon adjacent to the pyrrolidine ring.

As is shown in Scheme 2, compound **3** is obtained together with 1,2-dimethylpyrrolidino[3,4:1,2][60]fullerene (**15**) as the main reaction product (40% yield; 49% yield based on consumed C_{60}) as a result of the loss of sulfur from **14** or **3**. Interestingly, compound **15** has recently been obtained in 39% yield by heating C_{60} with sarcosine ethyl ester hydrochloride and Et_3N in *o*-dichlorobenzene (*o*-DCB) at 220 °C under dark and aerobic conditions through a mechanism involving radical species.[17] Although the mechanism for the formation of compound **15** lacking the thiol moiety from **14** is not clear, other related cases, probably involving a radical mechanism, have been reported in the literature.[18] It is worth mentioning that although compound **15** was not the goal in this reaction (C_{60}, **12**, and **13**), it does provide a facile access to 2-methyl-substituted pyrrolidinofullerenes which would otherwise require the presence of acetaldehyde as a reagent in Prato's protocol.

The redox properties of the novel compound **3** were studied by cyclic voltammetry (CV) in *o*-DCB/MeCN (4:1) as solvent at room temperature using tetrabutylammonium perchlorate as the supporting electrolyte (see the Supporting Information). The redox potentials are strongly influenced by the saturation of the fullerene double bonds, which results in a rise in the LUMO energy level.[19] Thus, the reduction waves are shifted towards more negative potentials (cathodic shift), which results in a slightly poorer accepting ability, as occurs in *N*-methylfulleropyrrolidine,[20] compared with pristine [60]fullerene.[21]

Thiophene-fused pyrrolidino[3,4:1,2][60]fullerene **3** exhibits three quasi-reversible reduction waves (–0.913, –1.299, and –1.652 V; Figure 2) that are cathodically shifted in comparison with pristine C_{60} (–0.806, –1.223, and –1.687 V). Interestingly, these values are similar to those of *N*-methylpyrrolidinofullerene under the same experimental conditions (–0.903, –1.301, and –1.841 V) despite the saturation of a second fullerene double bond in **3**. These experimental findings can be accounted for by the presence of the electronegative sulfur atom, which compensates to some extent the saturation of the second fullerene double bond in **3**, resulting in reduction potentials similar to those observed for the [60]fullerene monoadduct.[21] This electrochemical behavior is analogous to that observed for the re-

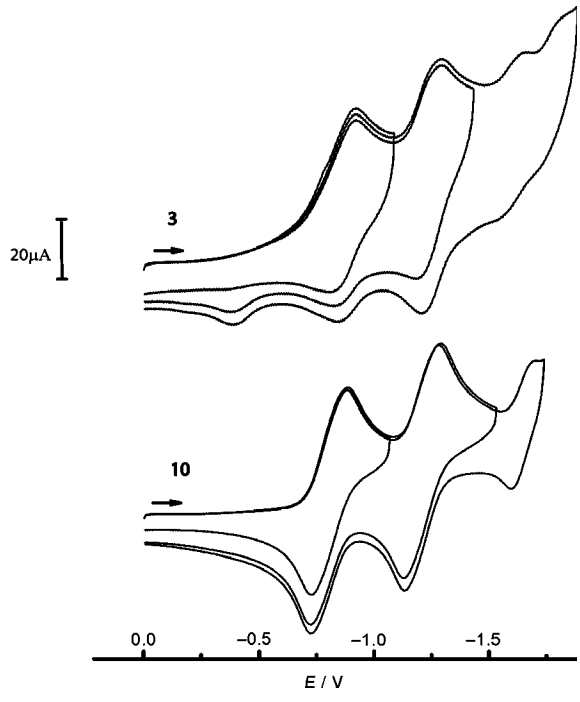


Figure 2. Cyclic voltammograms of compounds **3** and **10** measured in *o*-DCB/MeCN (4:1) at 100 mV s^{-1}.

lated compound **2** in which the sulfur atom is substituted by an oxygen atom (E_{red} = –0.923, –1.321, and –1.951 V).[10]

To validate the above electrochemical measurements, the redox potentials of compound **10**, in which only one double bond of the fullerene core is saturated, were also studied by cyclic voltammetry under the same experimental conditions. As expected, the values obtained (E_{red} = –0.874, –1.282, and –1.699 V) were similar to those of the *N*-methylfulleropyrrolidine. The slightly lower values observed could also be explained by the presence of the electron-withdrawing methoxycarbonyl group connected to the pyrrolidine ring.

In a previous paper, the intramolecular nucleophilic addition of the hydroxy group of the 1,3-dipole substituent to the fullerene surface was explored both experimentally and theoretically by the ONIOM approach.[10] In this study, the 1,3-dipolar cycloaddition of the 1,3-dipole bearing a thiol substituent instead of a hydroxy group followed by nucleophilic attack of the SH group to a [6,6] bond of C_{60} has been studied in detail. The difference in reactivity found for the hydroxy and thiol groups is compared and discussed.

The previously reported mechanism for the nucleophilic addition reaction in the case of the hydroxy substituent is shown in Figure 3 along with the relative energies and Gibbs free energies of the TSs, intermediates, and products.[10] The corresponding energy profile for the thiol substituent is depicted in Figure 4.

The 1,3-dipolar cycloaddition reaction between the azomethine ylide and C_{60} is thermodynamically extremely favorable in both cases, the reaction energies calculated with respect to the separated reactants being –48.3 and –47.7 kcal mol^{-1} for the hydroxy and thiol groups, respectively. The TSs for the cycloaddition reaction are more stable than the isolated reactants (–5.3 and –6.9 kcal mol^{-1} for OH and SH cases), although the activation barriers in terms of Gibbs free energies are endothermic (7.2 and 5.7 kcal mol^{-1} for OH and SH, respectively), as a reactant complex is formed in both cases (**Int1a** and **Int1b**).

These intermediates are –5.9 and –7.1 kcal mol^{-1} more stable than the corresponding isolated C_{60} and 1,3-dipole for OH and SH, respectively. Interestingly, the cycloaddition reaction for the thiol is slightly more favored as the activation barrier is somewhat smaller (approximately 0.5 kcal mol^{-1}) than for the OH group. Figure 5 describes the concerted but asynchronous reaction of **TS1b** along with the most important distances and angles.

Performing an intrinsic reaction coordinate (IRC) study of these large systems is a computationally very demanding

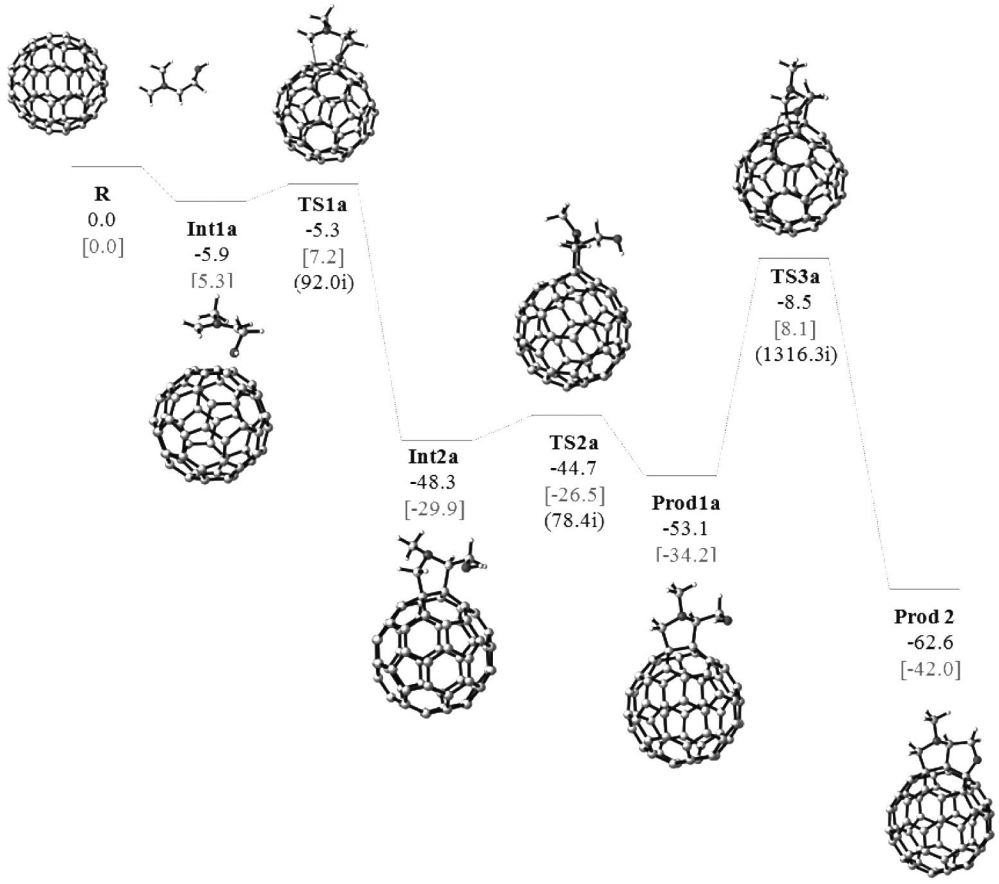


Figure 3. ONIOM2[B3LYP/6-31G(d):SVWN/STO-3G] reaction energy profile (Gibbs free energies in square brackets and the imaginary frequencies of the transition states in parentheses) for the reaction of C_{60} and the azomethine ylide bearing a CH_2OH substituent. Energies in kcal mol^{-1} and frequencies in cm^{-1}. Values are taken from ref.[10].

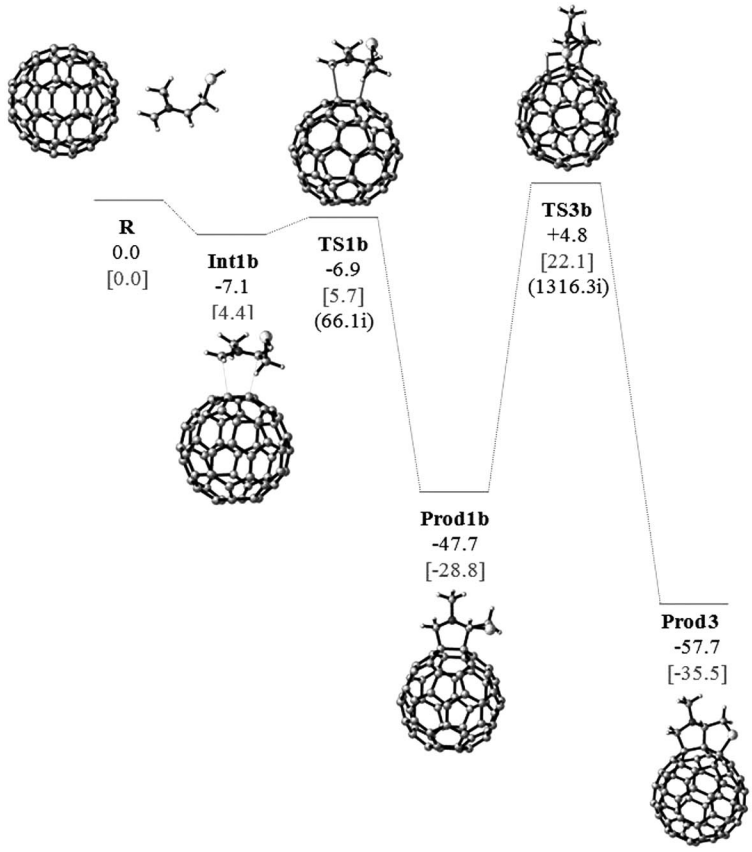


Figure 4. ONIOM2[B3LYP/6-31G(d):SVWN/STO-3G] reaction energy profile (Gibbs free energies in square brackets and the imaginary frequencies of the transition states in parentheses) for the reaction of C_{60} and the azomethine ylide bearing a CH_2SH substituent. Energies in kcal mol^{-1} and frequencies in cm^{-1}.

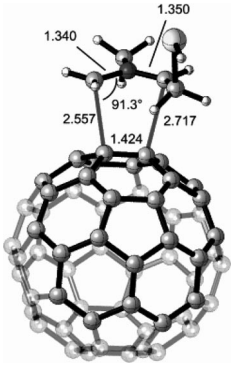


Figure 5. ONIOM2[B3LYP/6-31G(d):SVWN/STO-3G] **TS1b**-optimized structure with the most important distances and angles (in Å and degrees, respectively). The atoms treated at a high level in the ONIOM approach have been darkened.

task. However, full optimization of each transition state has been performed by slightly shifting the geometry of the transition state towards either the reactants or the products following the direction of the transition vector. By using this strategy, the TS for the 1,3-dipolar cycloaddition in the case of OH was shown to connect **Int1a** with **Int2a** (instead of the most favorable cycloaddition product **Prod1a**). The difference in stability of **Prod1a** with respect to **Int2a** is basically a result of the formation of a weak hydrogen bond between the hydrogen atom of the hydroxy group and the nitrogen atom of the pyrrolidino ring (the H–N distance is 2.226 Å).[10] However, this does not occur in the case of the thiol as **TS1b** leads directly to the most favorable cycloaddition product **Prod1b**. As happens in **Prod1a**, a hydrogen bond is formed between the hydrogen atom of the thiol group and the nitrogen atom of the pyrrolidino ring. However, the latter interaction is weaker than in the OH case as the H–N distance is larger (2.413 Å, see Figure 6, as compared with 2.226 Å for OH).

The 5-*exo*-*trig* cyclization corresponding to the nucleophilic attack of the thiol group on the fullerene is exothermic by –10.0 kcal mol^{-1} (–6.7 kcal mol^{-1} in terms of Gibbs free energies). The same reaction with a hydroxy group has a reaction energy of –9.5 and –7.8 kcal mol^{-1}, respectively.[10] Although the difference in the reaction energies for OH/SH is minor, the activation barrier for SH ($\Delta G^{\ddagger}$ = 50.9 kcal mol^{-1}) is about 8 kcal mol^{-1} higher in energy than that for OH ($\Delta G^{\ddagger}$ = 42.3 kcal mol^{-1}). Therefore, the main differences in reactivity observed experimentally are a result of the substantially higher activation barrier that has to be surmounted to finally achieve the cyclic product **Prod3**. Figure 6 shows the optimized structures of **Prod1b**, **TS3b**, and

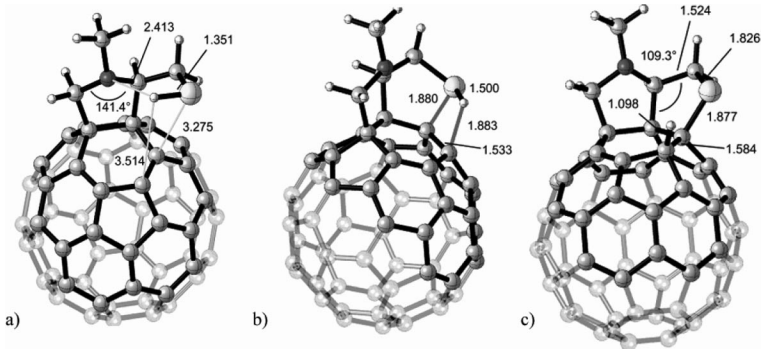


Figure 6. ONIOM2[B3LYP/6-31G(d):SVWN/STO-3G] optimized structures for a) **Prod1b**, b) **TS3b**, and c) **Prod3** with the most important distances and angles (in Å and degrees, respectively). The atoms treated at the high level in the ONIOM approach have been darkened.

Prod3 along with the most important distances and angles. In **TS3b**, the sulfur atom of the 1,3-dipole substituent is 1.880 Å from the carbon atom to which it will be finally attached. This distance is substantially longer than that for the OH group (1.579 Å), but is in accord with the longest C–S distance (1.877 Å) and the shortest C–O distance (1.439 Å)[10] found in the final products **Prod3** and **Prod2**, respectively. To analyze the reason for the higher barrier in the case of the thiol substituent, we calculated the increase in the deformation energy of the 1,3-dipoles and of the C_{60} fragments on going from **Prod1** to **TS3**. The deformation energy is defined as the energy needed to modify the geometry of the free reactants to attain the geometry they have in a TS or a given intermediate. We found that deformation of the separated 1,3-dipole and C_{60} fragments on going from **Prod1a** to **TS3a** requires 2.3 kcal mol^{-1} more energy (37.0 vs. 34.7 kcal mol^{-1}) than the transformation of **Prod1b** to **TS3b**. Therefore, the deformation energy does not explain the higher barrier in the 5-*exo*-*trig* cyclization for the SH case (actually you need less deformation energy in this case). Thus, one can conclude that the interaction energy between the two deformed fragments is mainly responsible for the lower barrier found for **TS3a** compared with **TS3b**. This can be the result of better overlap between the lone-pair orbitals of O, which are less diffuse than those of S, and the π system of the cage. In addition, the greater negative charge on the O atom in **Prod1a** (–0.357 e) compared with the charge on the S atom in **Prod1b** (–0.151 e) may also help the attack on the electron-deficient cage.

In summary, our theoretical study has shown that the reaction mechanisms found for both OH and SH systems are approximately the same. The 1,3-dipolar cycloaddition between the azomethine ylide bearing either a thiol or a hydroxy group and C_{60} is highly favored (the activation barrier is slightly more favorable for SH). The main differences in reactivity can be attributed to the activation barriers for the 5-*exo*-trig cyclization reaction. Although both processes present exothermic reaction energies, the activation barrier for the nucleophilic attack of the thiol group on the fullerene surface has been found to be substantially higher than the attack of the OH group (the activation barrier is about 8 kcal mol^{-1} higher for SH than for OH).

Conclusions

The first example of an intramolecular nucleophilic addition of a thiol group on the fullerene double bond adjacent to a fused pyrrolidine ring has been reported. This reaction occurs in a totally regioselective manner to afford the *cis*-1 isomer. In contrast to the previous example with alcohols, which leads to the formation of the oxygen pentagonal ring (tetrahydrofuran) in relatively good yields, the formation of the sulfur analogue (tetrahydrothiophene) is less favored, occurring spontaneously in a one-step synthesis in a very low yield.

Theoretical calculations (DFT and the ONIOM approach) predict that the formation of the sulfur pentagonal ring is favored and does not present structural constraints. However, the activation barrier for nucleophilic attack of the thiol group on the fullerene surface to form the thiophene ring is substantially higher than that previously reported for the formation of the furan from the hydroxy group (activation barrier difference of 8 kcal mol^{-1}), thus accounting for the poorer formation of tetrahydrothiophene **3**. Fullerene **3** is formed in competition with 1,2-dimethylpyrrolidino[3,4:1,2][60]fullerene (**15**), which is formed as the main reaction product by loss of the SH group, probably through a radical process.

Experimental Section

Computational Details: The Gaussian 03 suite of programs[22] was used to carry out full geometry optimizations within the two-layered ONIOM approach.[23,24] The density functional theory (DFT) SVWN method[25,26] with the standard STO-3G basis set[27] was used for the low-level calculations and the hybrid density functional B3LYP method[28–30] with the standard 6-31G(d) basis set[31,32] was employed for the high-level system. Spin-restricted formalism was used in all systems. The choice of DFT methods was basically motivated by the results of previous studies that showed that DFT [in particular B3LYP/6-31G(d)] gives reasonable descriptions of the reaction mechanism of pericyclic reactions.[33–40] All stationary points were characterized by computing the analytical vibrational frequencies to have one imaginary frequency corresponding to the approach of both reacting molecules in the case of transition states (TSs) and zero for all minima structures. Moreover, unscaled zero-

point energies (ZPEs) as well as thermal corrections and entropy effects using the standard statistical mechanics relationships for an ideal gas were calculated at 298 K to produce Gibbs free energies.[41] Atomic charges were analyzed by using the Mulliken population analysis.[42]

Preparation of Compound 10: A solution of Et_3N (101 mg, 1 mmol) and cysteine methyl ester hydrochloride (171.65 mg, 1 mmol) was stirred at room temperature for 30 min and then this mixture was added to a solution of formaldehyde (30 mg, 1 mmol) and C_{60} (180 mg, 0.25 mmol) in chlorobenzene (150 mL) and heated at reflux overnight. After cooling to room temperature, the solvent was removed in vacuo and the crude product was purified by flash chromatography over silica gel using CS_2 as eluent (to separate the unreacted fullerene) and then toluene/hexane (3:2) to obtain the product **10** in 7% yield (35% yield based on consumed C_{60}). ^{1}H NMR (298 K, $CDCl_3$, 500 MHz): δ = 3.88 (s, 3 H, CH_3), 4.26 (d, J = 10.8 Hz, 1 H, CH_2S), 4.31 (d, J = 10.8 Hz, 1 H, CH_2S), 4.61 (d, J = 9.7 Hz, 1 H, NCH_2S), 4.75 (d, J = 9.5 Hz, 1 H, CH_2N), 4.89 (d, J = 9.5 Hz, 1 H, NCH_2S), 4.98 (d, J = 9.7 Hz, 1 H, CH_2N) ppm. ^{13}C NMR ($CDCl_3$, 125 MHz): δ = 53.7, 57.5, 64.6, 68.5,69.53, 90.4, 136.0, 137.8, 137.83, 139.9, 140.1, 140.8, 140.9, 141.1, 142.1, 142.14, 142.2, 142.3, 142.5, 142.56, 142.6, 142.64, 142.7, 142.71, 143.1, 143.2, 143.21, 143.24, 143.5, 143.6, 144.8, 144.9, 144.91, 145.0, 145.2, 145.7, 145.8, 145.83, 145.84, 145.9, 146.1, 146.13, 146.17, 146.2, 146.23, 146.3, 146.5, 146.6, 146.61, 146.65, 146.7, 146.8, 146.85, 146.9, 147.0, 147.8, 147.9, 151.0, 151.1, 153.9, 155.3, 170.5 ppm. FTIR (KBr): $\tilde{\nu}$ = 526, 738, 1120, 1262, 1734 cm^{-1}. MS (MALDI-TOF): m/z = 880 $[M + 1]^+$.

Preparation of Compound 3: A mixture of 1,4-dithiane-2,5-diol (**13**; 25.88 mg, 0.17 mmol), C_{60} (250 mg, 0.34 mmol), and sarcosine (123.6 mg, 1.38 mmol) in chlorobenzene (150 mL) was heated at reflux for 1 h 30 min. After cooling to room temperature, the solvent was remove in vacuo and the crude product was purified by flash chromatography over silica gel using initially CS_2 as eluent (to separate the unreacted fullerene) and then CS_2/CH_2Cl_2 (9:1) to obtain the product **3** in 7% yield (9% yield based on consumed C_{60}). ^{1}H NMR (298 K, $CDCl_3$, 700 MHz): δ = 2.89 (s, 3 H, CH_3), 3.72 (dd, J = 13.6, 3.3 Hz, 1 H, CH_2S), 3.76 (dd, J = 13.6, 1.3 Hz, 1 H, CH_2S), 4.01 (d, J = 9.0 Hz, 1 H, CH_2N), 4.04 (m, 1 H, CHS), 4.76 (d, J = 9.0 Hz, 1 H, CH_2N), 6.47 (s, 1 H, C_{60}-H) ppm. ^{13}C NMR ($CDCl_3$, 175 MHz): δ = 39.6, 60.7, 65.6, 66.0, 67.4, 69.5, 78.2, 86.7, 128.4, 133.6, 134.7, 135.8, 136.2, 138.9, 141.1, 141.2, 141.3, 141.6, 142.2, 142.4, 142.6, 142.8, 142.86, 142.9, 143.0, 143.5, 143.8, 143.9, 144.0, 144.1, 144.18, 144.2, 144.3, 144.5, 144.6, 144.7, 145.0, 145.2, 145.3, 145.5, 145.7, 145.8, 145.83, 146.4, 146.5, 147.09, 147.1, 147.2, 147.9, 148.2, 148.3, 148.4, 148.6, 149.0, 149.2, 149.3, 151.5, 152.3 ppm. FTIR (KBr): $\tilde{\nu}$ = 526, 796, 1115, 1240, 1461 cm^{-1}. MS (MALDI-TOF): m/z = 823 $[M]^+$.

Supporting Information (see also the footnote on the first page of this article): ^{1}H and ^{13}C NMR and MS spectra for all compounds, reduction potentials, *x*-, *y*-, and *z*-optimized Cartesian coordinates for all minima and located transition states.

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