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Graphical Abstract





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Unusual multistep reaction of $C_{70}Cl_{10}$ with thiols producing $C_{70}[SR]_5H$

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ABSTRACT

We report a reaction of the chlorofullerene $C_{70}Cl_{10}$ with thiols producing $C_{70}[SR]_5H$ with all organic addends attached around one central pentagon at the pole of the C_{70} cage. This reaction was shown to proceed via a complicated radical pathway, presumably involving addition, substitution, rearrangement and/or elimination steps. The obtained $C_{70}[SR]_5H$ products were shown to be very unstable and undergo quantitative decomposition to pristine C_{70} , RSSR and RSH at elevated temperatures (e.g. 50 °C). Quantum chemical calculations and NMR spectroscopy data showed that cleavage of organic addends from the fullerene cage could be induced by solvation effects in solution.

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1. Introduction

Radical reactions ESR spectroscopy DFT calculations

Chlorinated fullerenes can be easily synthesized with high selectivity and excellent yields from the parent C_{60} or C_{70} compounds.¹⁻⁴ They represent very promising precursor compounds which can be converted to many different functional derivatives using halogen substitution reactions.

The chemistry of halogenated fullerenes was pioneered by Taylor and co-workers who revealed that chlorofullerene $C_{60}Cl_6$ reacts with C- and O-nucleophiles such as aromatic hydrocarbons in the presence of Lewis acids, MeLi, $H_2C=CH-CH_2Si(CH_3)_3$ and alcohols.⁵⁻⁹ More recently we have shown that highly selective reactions of $C_{60}Cl_6$ could be used for the efficient synthesis of watersoluble fullerene derivatives bearing amine, carboxylic and phosphonic acid groups as well as a number of other compounds.¹⁰⁻¹⁴

The chemistry of $C_{70}Cl_{10}$ remains less investigated which might be related to its lower availability and decreased molecular symmetry. Taylor and co-workers achieved the synthesis of $C_{70}Me_8$, $C_{70}Ph_8$, $C_{70}Ph_9OH$, and $C_{70}Ph_{10}$ from $C_{70}Cl_{10}$.¹⁵⁻¹⁸ We have reported the preparation of water-soluble carboxylic acid derivatives of [70]fullerene and its phosphorous-containing derivatives $C_{70}[PO(OEt)_2]_nH_n$ (n=1, 2).¹⁹⁻²⁰

Direct addition of various reagents (radicals or ion radicals) to the carbon cage of pristine [70]fullerene was used to prepare derivatives bearing hydrogen,²¹ aryl,²² *tert*-butoxyperoxide,²³⁻²⁴ amine²⁵ or trifluoromethyl²⁶⁻²⁷ groups.

Herein, we report an unprecedented reaction of $C_{70}Cl_{10}$ with thiols in the presence of organic bases (tertiary amines).

2. Results and discussion

We have shown that chlorofullerene $C_{70}Cl_{10}$ reacts with thiols in the presence of tertiary amines leading to the cleavage of all halogen atoms from the equator of the molecule and addition of five sulfide groups and one proton to different positions of the carbon cage (Scheme 1).



This reaction demonstrated reasonably high selectivity. Thus, treatment of $C_{70}Cl_{10}$ with the methyl ester of 2-mercaptopropionic acid produced compound **1a** (35-40%), traces of compound **2a** and considerable amounts of pristine C_{70} (40-60%) as a major side product.

The molecular compositions of **1a** and **2a** were confirmed by ESI mass spectrometry (see ESI Fig. S1, S4). The molecular structure of **1a** was deduced from the NMR spectra (Fig. 1 and ESI S2-S3). Thus, the ¹H NMR spectrum (Fig. 1a) exhibited a set of signals corresponding to three types of symmetrically nonequivalent organic addends in a 2:2:1 ratio. The signal of the new proton attached to the carbon cage appeared at 4.88 ppm. It was 2

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notable that similar spectra were previously obtained for $C_{60}(SR)_5H$ derivatives of [60]fullerene.¹³ Therefore, we can conclude that the reactions of $C_{60}Cl_6$ and $C_{70}Cl_{10}$ with thiols proceed in the same way and produce isotypical products. Indeed, the ¹³C NMR spectrum obtained for **1a** (Fig. 1b) conforms with the C_s molecular symmetry of this compound.





It should be emphasized that there are two possible isomers of $C_{70}(SR)_5H$ with C_s symmetry, "side-on" and "pole-on" addend arrangement (Fig. 1c), which satisfy all the spectroscopic data. However, DFT calculations carried out for the simplest model $C_{70}(SR)_5H$ molecule (R=Me) showed that the "side-on" isomer (ESI Fig. S5) was considerably less stable (by ~20 kcal/mol) compared to the "pole-on" structure.

In view of the fact that compound **1a** is formed from $C_{70}Cl_{10}$ *via* a sequence of multiple addition, elimination and rearrangement steps (called "addend dance"), one can expect realization of thermodynamic control in this reaction. Similar "addend dance" reactions known for fullerenes also produce the most thermodynamically stable products.²⁸⁻²⁹ Additionally, the low energy barrier for addend elimination from the cage (see below) also supports the idea that only the most thermodynamically

stable "pole-on" structure 1 can "survive" under the reaction conditions and avoid transformation to pristine C_{70} .

Compound **1a** demonstrated rather intriguing behavior. First of all, it underwent quantitative decomposition to C_{70} , RSH and RSSR at slightly elevated temperatures (50-60 °C, Scheme 2). Moreover, such decomposition also occurred with a solid powder of **1a** at room temperature within a few weeks. Most remarkable was the fact that cleavage of the organic addends from the fullerene cage in $C_{70}(SR)_5H$ could be induced simply by solvation. In particular, dissolving a portion of **1a** in a $CS_2/acetone-D_6$ mixture contaminated with traces of moisture produced NMR spectra characteristic for a highly symmetrical D_{5h} [70]fullerene molecule and low molecular weight by-products: RSH and RSSR (ESI Fig. S6-S7). Similar decomposition also occurred in low concentration solutions of **1a** even in dry solvents which did not allow us to obtain UV-VIS spectra of this compound.



Scheme 2 Facile decomposition of 1a

The experimentally observed instability of $C_{70}(SR)_5H$ is caused by the low energy cost for elimination of the thiol molecule which amounts to 11.1 kcal/mole in the case of MeSH. Water catalyzes this process for two reasons: (i) solvation of the thiol diminishes the energy costs for the RSH elimination step, and (ii) realization of the water-assisted H-transfer to the SR substituent on the fullerene cage (avalanche mechanism) has a barrier. Transformation of low energy the adduct C₇₀(SMe)₅H(H₂O) (ESI Fig. S8) into C₇₀(SMe)₄(H₂O)(HSMe) (ESI Fig. S9) requires 8.0 kcal/mol and has an energy barrier of 15.3 kcal/mol. The calculated structures of the transition states are shown in Figure 2a.



Figure 2. Computed molecular structures of the transition states. Small open circles and larger shadowed ones define H and O atoms, respectively. Key distances are given in Å.

However, in the presence of an additional water molecule the formation of the ionic structure $H_5O_2^{+}[C_{70}(SMe)_5]^{-}$ (ESI Fig. S10) from $C_{70}(SMe)_5H(H_2O)_2$ (ESI Fig. S11) requires only 5.0 kcal/mol and has small energy barrier of 7.2 kcal/mol (Figure 2b). The energy of this structure is practically the same as the energy of the neutral isomer $C_{70}(SMe)_4(MeSH)(H_2O)_2$ (ESI Fig. S12) and the energy of the transition state corresponding to the H

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atom transfer inside the $H_5O_2^+$ moiety (ESI Fig. S13). Elimination of the RSH molecule induces the following reactions of decomposition of **1** with elimination of two disulfide molecules MeSSMe with energy gains of 11.3 and 17.6 kcal/mol for the first and second steps, respectively.

Thus, the results of the DFT calculations emphasized the generally low stability of the $C_{70}(SR)_5H$ compounds. Indeed, a facile solvation-induced degradation was observed not just for **1a**, but also for a number of other compounds **1b-d** which we attempted to prepare, isolate and characterize (Scheme 1). ESI mass spectrometry proved that chromatographically isolated fractions represented toluene solutions of the target **1b-d** compounds (ESI Fig. S14-S17). However, all attempts to concentrate these solutions under vacuum and obtain solid samples suitable for NMR characterization were not successful due to almost complete degradation of these compounds to C₇₀.

The observed surprisingly low stability of the $C_{70}(SR)_5H$ compounds might prevent their practical application. However, the examined reaction of $C_{70}Cl_{10}$ with thiols is fundamentally interesting. The fact that 10 chlorine atoms are replaced with 6 new substituents in **1a** suggests that the investigated reaction involves redox processes when $C_{70}Cl_{10}$ or some latter intermediate undergoes partial or complete reduction with RSH forming RSSR and HCl (trapped as a salt with the amine). We emphasize that none of the incoming RS- groups or hydrogen atom attach to the positions which were previously occupied by chlorine atoms in $C_{70}Cl_{10}$ which points to a complicated multistep reaction mechanism.

In order to shed light on a general nature of the investigated reaction, we applied ESR spectroscopy using 5,5-dimethyl-1pyrroline *N*-oxide (DMPO) as a radical trap. The ESR spectrum of the RSH–DMPO–(*i*Pr)₂EtN mixture showed a rather weak signal for a radical impurity which was also detected in the solution of DMPO alone (Figure 3). However, the addition of $C_{70}Cl_{10}$ to the RSH– (*i*Pr)₂EtN mixture resulted in the appearance of a strong multi-line signal which could be attributed to a radical species, which was formed as a reaction intermediate trapped with DMPO. We believe that this signal corresponds to the adduct of DMPO with the RS⁻ radical since a very similar ESR spectrum was previously reported.³⁰



Figure 3. ESR spectra of the RSH–DMPO– $(iPr)_2$ EtN system (weak signal due to an impurity is visible) and the reaction mixture (RSH–DMPO– $(iPr)_2$ EtN +C₇₀Cl₁₀) in toluene.

The obtained experimental and spectroscopic data allowed us to propose a tentative mechanism of the reaction of $C_{70}Cl_{10}$ with thiols (Scheme 3). We assume that the first step of the reaction is

a single electron transfer from the RSH molecule to $C_{70}Cl_{10}$. This assumption is reasonable since $C_{70}Cl_{10}$ is known as a strong electron acceptor, while RSH behaves as a good electron donor. The radical anion [C₇₀Cl₁₀]⁻ is rather unstable and, therefore, eliminates Cl⁻ and forms the [C₇₀Cl₉]⁻ radical. At the same time, the thiol radical cation stabilizes via elimination of a proton forming the RS⁻ radical. Recombination of the [C₇₀Cl₉]⁻ and RS⁻ radicals can produce C70Cl9SR which is a product of the substitution of one chlorine atom in C₇₀Cl₁₀ with a sulfide group. The presented sequence of steps demonstrates realization of the desired reaction pathway (I) leading to the target substitution products. However, the intermediate $[C_{70}Cl_9]$ radical can be further reduced with another RSH molecule to the corresponding anion which eliminates Cl⁻ and forms C₇₀Cl₈. This represents a competing reaction pathway (II) leading to the reduction (chlorine elimination) products. It seems that pathway (II) is favorable in the case of $C_{70}Cl_{10}$ which explains the formation of C₇₀(SR)₅H (partial elimination - partial reduction product) and $C_{70}\ as$ the major side product resulting from the complete reductive elimination of addends from the fullerene cage.



Scheme 3. Proposed SET mechanism of the reaction of C70Cl10 with thiols

The regiochemistry of the reaction of $C_{70}Cl_{10}$ with thiols is very interesting. We believe that the spin density in the $[C_{70}Cl_9]$ and intermediate $[C_{70}X_n]$ (X=Cl or SR) radicals is delocalized between multiple centers on the C_{70} cage. It is known that attachment of nitrogen-centered radicals occurs near the central pentagon at the pole of the C_{70} cage.²⁵ Additionally, the reaction of $C_{70}Cl_{10}$ with P(OEt)₃, proceeding *via* a radical pathway, also produced two compounds bearing organic addends attached at the poles of the C_{70} cage.²⁰ Considering these experimental facts it is reasonable to assume that the spin density in the $[C_{70}X_n]$ radicals is high enough at the poles of the cage in comparison with the equator positions which explains the revealed arrangement of the sulfide groups in **1a**. It is also likely that competition between pathways (I) and (II) produces a $[C_{70}(SR)_5]$ radical which undergoes further reduction with the formation of stabilized

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cyclopentadienyl-type anion $[C_{70}(SR)_5]^{-}$. This anion undergoes protonation during workup and chromatography on silica which results in isolation of the target products $C_{70}(SR)_5H$ such as 1a.

The mechanism of the primary reaction between C₇₀Cl₁₀ and RSH was also analyzed using DFT calculations and the corresponding discussion is provided in the ESI. Briefly, the computational results supported our hypothesis concerning the possibility of the attachment of RS groups to several favorable locations on the carbon cage besides the one bearing the leaving chlorine atom. At the same time, the formation of the cyclopentadienyl moiety surrounded by five RS groups was shown to be a driving force of the process producing thermodynamically favorable product **1** (Scheme 1).

We emphasize that the proposed radical substitution mechanism shown in Scheme 3 conforms with all experimental results including the ESR observation of the RS⁻ radicals trapped with DMPO. We strongly believe that the previously reported reaction of $C_{60}Cl_6$ with thiols¹³ also proceeds via a radical mechanism similar to the one outlined in Scheme 3. Indeed, ESR spectroscopy revealed virtually identical radical species trapped with DMPO in the system C₆₀Cl₆+RSH+R'₃N (ESI Fig. S17). However, the substitution pathway (I) strongly dominates over the reduction pathway (II) in the case of C₆₀Cl₆ thus producing C₆₀(SR)₅H products with an excellent selectivity. This might be a consequence of the fact that the substituents occupy exactly the same positions on the C_{60} cage where the chlorine atoms were attached in the parent $C_{60}Cl_6$.

3. Conclusion

In conclusion, we report a novel reaction of $C_{70}Cl_{10}$ involving thiols as reagents which possesses a radical nature as it was determined from ESR experiments. Unlike a previously known Friedel-Crafts arylation method producing mainly C70Ar8/10 derivatives, the investigated reaction proceeds through a more complicated pathway leading to complete detachment of the chlorine atoms from the equator of the carbon cage and addition of organic addends around one of the poles.

The obtained C70[SR]5H products were shown to be very unstable and undergo quantitative decomposition to pristine C_{70} , RSSR and RSH at elevated temperatures (e.g. 50 °C), under extended storage at room temperature or in solution due to solvation effects. The surprisingly low stability of C₇₀[SR]₅H compounds was rationalized using DFT calculations.

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Supplementary Material

Description of the experimental and DFT calculation procedures, Figures S1-S18.

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