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Theoretical investigation of the electronic structure of 1-(3,4; 3,5 and 3,6-bis-selenocyanato-phenyl) pyrrolidinofullerenes

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Abstract

The electronic structures and geometries of 1-(3,4; 3,5 and 3,6-bis-Selenocyanato-phenyl) pyrrolidinofullerenes were investigated theoretically using Density Functional theory at the B3LYP/3-21G∗ and B3LYP/6-31G∗ levels of theory. On all levels of theory the *ortho* isomer is predicted to be the most stable. The obtained optimized geometries, electronic properties and energetics of structural variables are discussed.
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1. Introduction

In recent years, there has been a continued interest in fullerene-based systems. These systems are expected to exhibit new interesting physical and chemical properties [1–4]. Many of the important physical, biological and pharmacological applications for such systems have already been demonstrated. The size of C_{60} molecule is similar to many biologically active molecules, including drugs and steroid hormones [5], therefore it may be efficiently used as a template for creating a variety of biologically active systems. C_{60} and related substances have shown biological activity, such as HIV-protease inhibition [6,7], DNA photocleavage [8], antibacterial agents [9] and radical scavengers [10].

Selenium and some of its organic derivatives have been shown to also exhibit biological activity. Many of organoselenium compounds have shown biological activity in numerous fields such as in the development of antibacterial, antiviral, antifungal, antiparasitic, antiinflammatory and antihistamine agents [11]. Organoselenium compounds which have selenocyanate groups show promising results in a variety of chemopreventative studies [12]. Some compound of this class studied earlier were Se-methylselenocysteine, *p*-methoxybenzeneselenol, benzylselenocyanate and 4-phenylenebis-(methylene)selenocyanate. These compounds have been used mostly as chemopreventive agents for human cancer and usually give good results against breast cancer [13–15].

C_{60}, as all fullerenes, is highly hydrophobic and insoluble, which causes significant problems in fullerene applications in biology and medical. Thus, several synthetic methodologies have been developed to functionalize the fullerene with polar functional groups to increase its dissolvability to water and polar solvents [16–18]. One of the most important fullerene functionalization is the formation of *N*-alkyl-fulleropyrrolidines by 1,3-dipolar cycloaddition of azomethine ylides to C_{60} [19]. On the other hand, the selenocyanate group is also a very polar group.

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Therefore the covalent binding of a phenyl ring containing selenocyante group to a fulleropyrrolidine moiety may gave rise to new fullerene-based systems which have new chemical and biological properties.

In this work we have investigated theoretically 1-(3,4; 3,5 and 3,6-bis-selenocyanato-phenyl)pyrrolidinofullerenes for the first time by performing Density Functional Theory (DFT) calculations. These correspond to *ortho* (1-(3,4-bis-selenocyanato-phenyl) pyrrolidinofullerenes), *meta* (1-(3,5-bis-selenocyanato-phenyl)pyrrolidinofullerenes), and *para* (1-(3,6-bis-selenocyanato-phenyl)pyrrolidinofullerenes) isomers which are shown in Fig. 1.

2. Computational details

All theoretical calculations in this work were performed using the computational methods implemented in the GAUSSIAN03 package [20]. The geometries of the compounds were optimized at the B3LYP/3-21G* and B3LYP/6-31G* levels of theory, however, frequencies were only computed using the B3LYP/3-21G* method [21,22]. Due to computational limitations we were unable to perform a B3LYP/6-31G* frequency calculation. In addition, NMR constants were evaluated using the IGAIM method using the geometries obtained at the B3LYP/6-31G* level of theory [23]. Moreover, the ONIOM method [24] with the fullerene described using the UFF force-field [25] was used to compare geometries, energies and frequencies to the full DFT optimizations. In our recent investigations on similar Se containing systems [26] we have found that the DFT-B3LYP method is able to accurately predict experimental parameters [27].

3. Results and discussion

The optimized B3LYP/6-31G* structures for the *ortho*, *meta* and *para* isomers are presented in Fig. 1. In the figure, the yellow spheres are C atoms, blue spheres are H atoms, red spheres are N atoms, and orange spheres are Se atoms. In addition B3LYP/3-21G* spectra for the three molecules are also presented.

Fig. 1 also shows the bond lengths and bond angles for each of the molecules. The general geometries of all three isomers are very similar (in all three computational approaches used), the major difference being the geometrical structure of the *ortho* structure. In this structure we see that the Se–Se distance (orange spheres in the figure) is ~3.2 Å, with a bond order between them of approximately 0.004. Interestingly, this is very similar to the Se–O bond order in *ortho* 2-Se-(2-methyl-2-propenyl)-1-benzoic acid [26] where the distance was 3.21 Å with a bond order of 0.0005. In the *para* and *meta* isomers the Se–Se distances are 5.8 and 6.6 Å, respectively. These bond distances are quite significant and yield bond orders essentially equal to 0.0. Therefore, we do not expect any stabilization of these structures resulting from Se–Se interactions. Generally speaking, the bond order is a relative value that is com-

puted based on Natural Bond Orbital (NBO) Analysis [28,29] that computes the interactions between various atoms in the molecule. These values are relative, and are meant to be analyzed quantitatively. Values of 0.0 and those below 0.001 signify that there is minimal interactions between the atoms of interest.

The calculated spectra suggest that the *para* isomer should have more intense modes, particularly in the 500–900 cm^{-1} and 1200–1500 cm^{-1} range. The modes in the first range correspond primarily to the vibrations of the five-membered ring attached to the fullerene. The latter vibrations correspond to internal motions in the six-membered phenyl ring attached to the pyrrolidinofullerene group. The most intense peaks in all the systems correspond to the CH rock mode of the six-membered phenyl ring, which can be seen at 1615 cm^{-1}. The basic vibrational modes are presented and assigned in Table 1. It is also interesting to note that the ONIOM method, while much less expensive from the computational point of view, gives very similar vibrational spectra with the maximum discrepancy of 35 cm^{-1}.

In addition to calculation of the vibrational modes for this molecule, we have also calculated IGAIM NMR shifts. While there are many shifts that can be discussed we will focus on the Se shifts since these are the ones that can be used to identify the molecules. For the *ortho* structure we should get two ^{77}Se shifts at 1494 ppm, and 1582 ppm, that correspond to the first and second Se–CN groups. The higher second value is probably due to the interaction of the first Se–CN group with the ring since it has the CN group pointing away from the plane which causes a change in the shift due to its interactions with the carbon atoms of the phenyl ring. For the *meta* structure one should observe two equivalent shifts at 1507 ppm. As for the final *para* structure we should observe at 1491 ppm and 1573 ppm, the latter being higher due to its closer proximity to the N atom of the five-membered ring (Se–N distance of 3.18 Å). It is interesting to note that while in the *ortho* isomer the Se–Se interaction causes the ^{77}Se shifts to lower, the Se–N interaction in the *para* structure is stronger as can be seen by the slightly lower shift (by ~3 ppm). This supports our initial assertion of strong Se interactions with electronegative atoms [26].

Table 2 has the HOMO/LUMO gaps, total energies, relative energies and corrected enthalpy differences. Table 3 shows the thermodynamic properties for the molecules in Fig. 1: entropy, heat capacity at constant pressure and enthalpy content at three different temperatures calculated using B3LYP/3-21G* frequencies. The fits were performed according to the equations implemented by the National Institute of Standards and Technology (NIST) [27]. For these calculations, the correct thermal energies shown in Table 2 (E^{corr}) are computed using the basic thermodynamic relationship, where the free energy changes are described as: $\Delta H - TS$, where ΔH is the enthalpy change, T is the temperature, and S is the entropy.

The results suggest that the HOMO/LUMO gap for the *meta* structure is the highest, while *para* structure has the

Fig. 1. Theoretical IR spectra (frequencies calculated at the B3LYP/3-21G* level of theory) and selected structural parameters with bond lengths shown in angstroms (Å) and bond angles in degrees (°) for the *ortho*, *meta*, and *para* structures calculated using the B3LYP/6-31G* method. In the structural diagrams, the yellow spheres are carbon, blue spheres are hydrogen atoms, orange spheres are selenium atoms and pink atoms are nitrogen atoms.

Table 1

Vibrational analysis (frequencies are shown in cm^{-1}) for each of the three structures with descriptions at the B3LYP/3-21G∗ level with ONIOM results also shown

Vibrational mode	Ortho	Ortho (ONIOM)	Meta	Meta (ONIOM)	Para	Para (ONIOM)
SeCN wag	78	76	75	77	70	72
SeCN twist	414	411	413	419	412	410
Se–C (CN) stretch	538	524	543	531	550	545
CC stretch (five membered ring, carbon atoms directly attached to C_{60})	916	912	917	916	911	901
CH$_2$ rock (five membered ring)	940	971	941	974	946	934
CC stretch (five membered ring)	1027	1021	1031	1022	1033	1029
CH twist (phenyl ring)	1211	1213	1219	1213	1218	1213
CH$_2$ twist (five membered ring)	1256	1261	1255	1261	1252	1261
C–N stretch (phenyl–five membered ring connection)	1412	1416	1391	1403	1394	1387
CH deformation (phenyl ring)	1464	1467	1466	1474	1394	1402
CN group stretch	2249	2276	2255	2281	2257	2280
CH stretch (five membered ring)	3131	3141	3113	3144	3179	3165
CH stretch (phenyl ring)	3253	3219	3251	3215	3222	3221

Table 2

Physical and chemical properties of the isomers

Physical property	Ortho	Meta	Para
HOMO/LUMO Gap	1.971	1.973	1.963
ZPE[a]	0.5216	0.5210	0.5212
B3LYP/3-21G∗	−7600.85818	−7600.84923	−7600.84700
B3LYP/3-21G∗ + ZPE	−7600.33658	−7600.32820	−7600.32580
B3LYP/6-31G∗	−7634.39277	−7634.38561	−7634.38270
B3LYP/6-31G∗ + ZPE[b]	−7633.87118	−7633.86457	−7633.86149
B3LYP/ONIOM	−5348.00966	−5348.06243	−5348.065767
B3LYP/ONIOM + ZPE	−5346.13245	−5348.12607	−5346.129578
$E^{3\text{-}21\text{G}*}$ (kcal/mol)	0.000	5.612	7.012
$E^{3\text{-}21\text{G}*}$ + ZPE (kcal/mol)	0.000	5.262	6.767
$E^{6\text{-}31\text{G}*}$ (kcal/mol)	0.000	4.497	6.322
$E^{6\text{-}31\text{G}*}$ + ZPE (kcal/mol)[b]	0.000	4.147	6.076
E^{ONIOM} (kcal/mol)	0.000	4.535	2.442
E^{ONIOM} + ZPE (kcal/mol)	0.000	4.004	1.804
$H(298.15\ K) - H(0)$ (kcal/mol)[c]	23.953	24.120	23.865
$H(1000\ K) - H(0)$ (kcal/mol)[c]	251.073	251.316	251.100
$S(298.15\ K)$ (cal/mol K)[d]	218.821	225.435	217.591
$S(1000\ K)$ (cal/mol K)[d]	582.283	589.037	581.233
E^{corr} (298.15 K) (kcal/mol)[e]	0.000	1.805	9.712
E^{corr} (1000 K) (kcal/mol)[e]	0.000	1.078	6.511

Total and relative energies were obtained at different levels of theory, while all other properties were calculated at the B3LYP/3-21G∗ level and are given in Hartrees if not indicated otherwise. E^{corr} are the corrected thermal energies (kcal/mol) at elevated temperatures, for which the fitted relationships are shown in Table 2.

[a] Zero-point correction.
[b] Values were obtained with the 6-31G∗ basis set, with frequencies calculated using the B3LYP/3-21G∗ method.
[c] Enthalpy corrections to electronic energy at different temperatures.
[d] Entropy corrections to electronic energies at different temperatures.
[e] Sum of electronic and thermal energies at different temperatures.

lowest gap. The large gap for *meta* isomer may be attributed to the reduced torsional potential and interaction between the substituted groups. On the other hand, the minor difference between the *ortho* and *meta* structures can be attributed to the fact that the *ortho* structure has a higher interaction between the selenium atoms.

In Table 2 the relative energies shown (kcal/mol) were calculated using the standard minimization procedures to which the zero-point energies (ZPE) corrections were added. We can see that the *meta* structure is 5.26 kcal/mol higher in energy than the *ortho* structure (calculated at the B3LYP/3-21G∗ level with ZPE corrections factored

in). Calculations using a larger basis set (6-31G∗) reduce the difference in the energy to 4.15 kcal/mol. For the *para* structure, we get a B3LYP/3-21G∗ energy difference of 6.77 kcal/mol and a B3LYP/6-31G∗ energy difference of 6.08 kcal/mol. The difference between the *meta* and *para* structures are around 1.51 kcal/mol and 1.93 kcal/mol at the B3LYP/3-21G∗ and B3LYP/6-31G∗ levels of theory, respectively. The ONIOM method predicts the most stable isomer correctly, but fails in predicting the higher relative stability of *meta* versus *para* isomer. It is interesting to note that the Se–Se interaction in the *ortho* system stabilizes the system. On the other hand, in the *para* structure, the sele-

Table 3
Thermodynamic properties of the molecule in Fig. 1, calculated using frequencies obtained at the B3LYP/3-21G* level, where C_p is the heat capacity in J mol^{-1} K^{-1}, S is the entropy in J mol^{-1} K^{-1}, and ΔH is the standard enthalpy kJ mol^{-1}

		Fitted thermodynamic equation ($T/1000 = t$)	100 K	298.15 K	1000 K
Ortho	C_p	$-436.04491 + 4997.09628*t - 4111.39706*t^2 + 1250.35778*t^3 + 1.60651*t^{-2}$	184.18	737.20	1702.03
	S	$-471.64203*\ln(t) + 5155.30348*t - 4342.99866 *t^2/2 + 1359.42255*t^3/3 - 2.07525/(2*t^2) - 999.6649$	476.84	915.55	2436.27
	ΔH	$-486.46091*t + 5227.73956*t^2/2 - 4460.40289*t^3/3 + 1420.64549*t^4/4 - 2.23285/t + 56.95444$	10.67	100.22	1050.49
Meta	C_p	$-434.59381 + 4991.9681*t - 4103.06737*t^2 + 1245.9908*t^3 + 1.61594*t^{-2}$	186.13	737.77	1702.36
	S	$-471.08205*\ln(t) + 5154.03017*t - 4340.20957 *t^2/2 + 1357.63716*t^3/3 - 2.09747/(2*t^2) - 970.92072$	503.07	943.22	2464.53
	ΔH	$-485.04148*t + 5222.33909*t^2/2 - 4451.03415*t^3/3 + 1415.45122*t^4/4 - 2.24756/t + 57.44323$	11.13	100.92	1051.51
Para	C_p	$-439.71864 + 5015.9021*t - 4136.35988*t^2 + 1260.84247*t^3 + 1.59901*t^{-2}$	181.40	737.11	1702.66
	S	$-475.53437*\ln(t) + 5175.58329*t - 4370.91873*t^2/2 + 1371.73164*t^3/3 - 2.0678/(2*t^2) - 1014.48227$	473.25	910.40	2431.88
	ΔH	$-489.36171*t + 5243.15119*t^2/2 - 4480.57463*t^3/3 + 1429.01511*t^4/4 - 2.21695/t + 56.87524$	10.53	99.85	1050.60

These where fitted to the Shomate equations, which are implemented by the JANAF tables of the NIST databases.

nium interaction with the nitrogen atom of the five-membered ring is unfavourable from the energetic point of view.

To consider temperatures above absolute zero, thermal corrections are needed to describe the system in a proper manner. We have also calculated the thermodynamic functions and extracted relative corrections at higher temperatures. Table 2 presents the vibrational zero-point energy (ZPE), the change in enthalpy ($H(T) - H(0)$) and the entropy at both 298.15 K and 1000 K, and Table 3 presents the Shomate equations used to derive these parameters. In the table E^{corr} are the sums of electronic and thermal energies, which are particularly useful when examining energy differences at elevated temperatures. As we can see at room temperature the E^{corr} values are higher than without thermal corrections, but at elevated temperatures the E^{corr} are closer to our originally proposed ZPE corrected values. Therefore, thermally corrected energies using the Shomate equation NIST method are very similar to our standard B3LYP energy differences.

4. Conclusions

In this work we have analyzed the theoretical structure, IR spectra, NMR structure and energetics of the ortho, meta and para forms of 1-(3,4; 3,5 and 3,6-bis-selenocyanato-phenyl) pyrrolidinofullerenes using the DFT-B3LYP method. We have shown that the ortho isomer is the lowest energy structure, with meta and para higher in energy than it by 4.15 kcal/mol and 6.08 kcal/mol, respectively at the B3LYP/6-31G* level of theory. These results suggest that the ortho isomer should be the dominant form, while meta and para isomers are expect to be present in an experimental medium in similar, but lower concentrations.

As in previous Se systems [26], the ability of Se to mediate charge on the molecule (as were calculated by observing the charges and electrostatic potentials for this system) may allow for it to have a crucial role in various biochemical mechanisms. This fact, can in turn allow for molecular stabilization of free radicals and other excess charge that is the cause of DNA mutations and subsequently cancer. Since Se can mediate charge (since these molecules have negative LUMO energies, which suggests a propensity towards electron attachment), these anions can be stabilized inhibiting the DNA damaging effects of radiation and free radicals in the body. Therefore these systems are potential candidates to be used to offset harmful radical interactions in the body and other charge effects.

The presented calculations are interesting from a fundamental point of view since they are systems that adequately reveal Se interactions in a novel fullerene derived molecule. Also, it is useful to mention that the fullerene undergoes slight geometric distortions as a result of substitution. This work can be useful for experimentalists to pursue the electronic structure of this molecule further. Unfortunately, calculations using more sophisticated methods are difficult due to the size of these molecular systems. It has been found, however, that the DFT methods are in relatively good agreement with MP2, CCSD (T) methods for molecules of this type [28].

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