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Fullerene (C_{20}) as a sensing material for electrochemical detection of Nortriptyline: A theoretical study

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ABSTRACT

Quantification of nortriptyline (NTP) as an antidepressant medicine is of great importance. Therefore, in this research, (NTP) adsorption on the surface of fullerene C_{20} was studied by density functional theory computations. The calculated adsorption energies showed NTP interaction with C_{20} is experimentally possible. The negative values of enthalpy alterations, Gibbs free energy changes and great values of thermodynamic constants indicated the adsorption process is spontaneous. The negative values of adsorption enthalpy changes revealed the interaction of NTP with fullerene is exothermic. The bandgap of fullerene after adsorption of NTP increased %296.410 from 1.950 (eV) to 7.730 (eV) indicating the electrical conductivity of fullerene experienced a very sharp alteration during the interaction process. Therefore, C_{20} can be used as a sensor for electrochemical detection of NTP. The influence of the temperature on the NTP interaction with fullerene was also investigated and the results showed the adsorption process is more favorable in the lower temperatures.

Introduction

Nortriptyline (NTP, Figure 1a), is a tricyclic antidepressant medicine that is prescribed for the treatment of depression, eating disorders, neuropathic pains, migraine prevention, nocturnal enuresis, fibromyalgia, insomnia, irritable bowel syndrome, anxiety disorders and attention deficit hyperactivity disorder [1-3]. NTP is one of the best-selling antidepressants that induces its therapeutic effects by inhibiting the uptake of norepinephrine and serotonin [4-6]. However, in high doses, NTP can be highly toxic and its adverse effects are agitation, drowsiness, coma, seizures and tachycardia. In this respect, NTP determination is very important. To date, various analytical techniques such as high-performance liquid chromatography (HPLC), gas chromatography (GC), fluorimetry, capillary electrophoresis and UV-Visible spectrophotometry have been reported for the quantitation of NTP [7-9].

However, these methods are too expensive, time-consuming and tedious. Besides, large amounts of organic solvents are used in the mentioned methods. But, electrochemical and thermal sensors are prominent alternatives for the refereed analytical techniques because these types of sensors are rapid, simple, economic, portable, selective and sensitive devices that can determine the amount of the analyte with excellent accuracy and repeatability [10-14]. However, the first step in the development of a new electrochemical and thermal sensor is to find a recognition element that interacts with the analyte selectively and this interaction should lead to a considerable change in the electrochemical and thermal conductivity of the utilized recognition element which is used as a signal for determination of the analyte concentration [15-17].

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On the other hand, fullerene (C_{20}, Figure 1b) is the smallest nanomaterial with a dodecahedral cage structure [18]. The structure of this fullerene is highly curved and it is composed of pentagonal rings. C_{20} has unique traits that make it an eminent sensing material like high conductance, great surface area/ volume ratio and excellent reactivity [19]. In this respect, the goal of this study is to evaluate the sensing performance of C_{20} for thermal and electrochemical detection of NTP by density functional theory simulations.

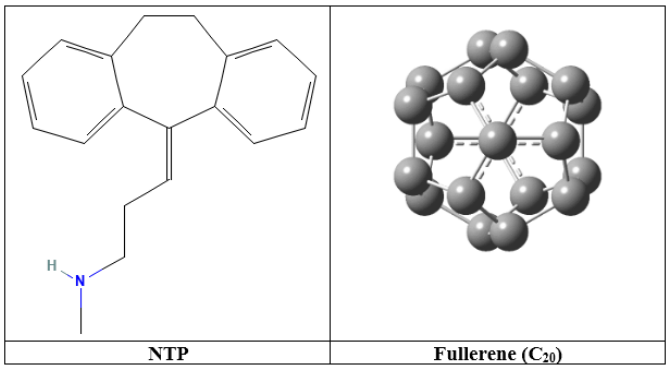

Figure 1. the chemical structure of NTP and C_{20}

2. Results and Discussion

In order to find the most stable configuration, the adsorption process was investigated at two different positions. As can be seen from the presented optimized structures of NTP-fullerene complexes at Figure 2, in A-Conformer, the nanostructure is inserted near the central three adjacent rings of NTP and in the B-Conformer, fullerene is placed near the amine group of NTP. The calculated total electronic energies in table 1, showed that B-Conformer is more energetically stable than A-Conformer. Besides, the computed adsorption energies indicated NTP interaction with the adsorbent is experimentally feasible and the adsorption process is more favorable at A-conformer. In order to obtain more information about the adsorption mechanism, the NBO computations were also carried out and the results showed no chemical bonds have been created between fullerene and NTP and the studied interaction is a physisorption [9-11].

The maximum (ν_{max}) and lowest vibrational frequencies (ν_{min}) of structures were also calculated by IR computations. As can be seen from Table 1, no negative frequency was observed for the studied structures. Therefore, all of the investigated structures are in a true local minimum [12].

The dipole moments of the structures were also computed. As the provided data at table 1 reveals clearly when NTP adsorbs on the surface of fullerene the dipole moment increases from 1.190 to 4.210 and 4.780 at A and B conformers respectively. Therefore, the solubility and bioavailability of NTP enhance significantly when it is adsorbed on the surface of fullerene [13].

Table 1. The structural parameters of NTP, C_{20} and their complexes

	Total electronic energy (a.u)	Adsorption energy (kJ/mol)	ZPE (kJ/mol)	ν_{min} (cm^{-1})	ν_{max} (cm^{-1})	Dipole Moment (Debye)
NTP	-776.656	---	1088.090	23.879	3970.181	1.190
C_{20}	-747.196	---	325.260	261.392	1690.640	0.000
A-Conformer	-1523.861	-23.194	1438.830	3.048	3970.193	4.210
B-Conformer	-1523.876	-62.831	1439.470	4.540	3969.992	4.780

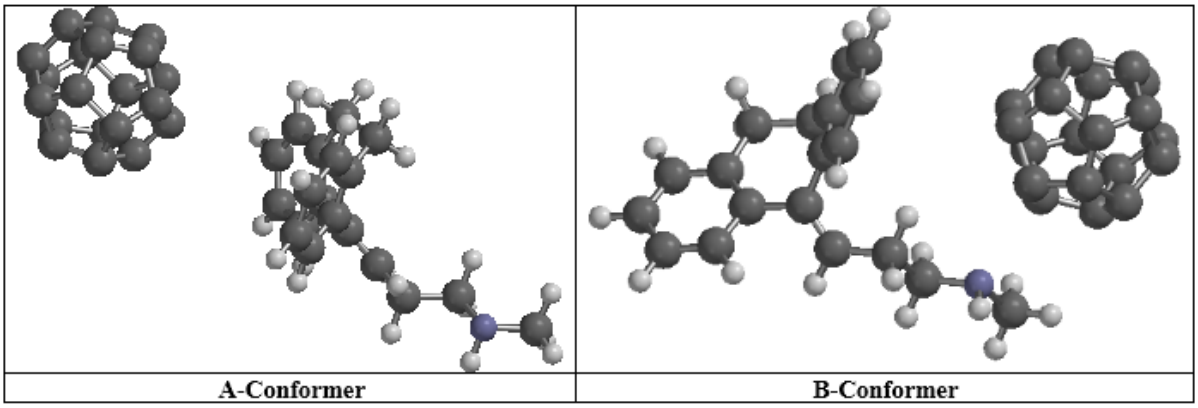

Figure 2. Optimized structures of NTP-C_{20} complexes

The thermodynamic parameters of NTP adsorption process were also calculated and the results are presented in Figure 3. As can be seen, the adsorption Gibbs free energy (ΔG_{ad}) is negative at both conformers which indicates the interaction process is spontaneous. The values thermodynamic equilibrium constants (K_{th}) are positive and little for both conformers that indicates the interaction is reversible and equilibrium. The impact of temperature on both parameters was also checked out and

the results demonstrates the interaction process is more favorable at lower temperatures [14].

The positive values of adsorption entropy changes (Δs_{ad}) showed the adsorption process is also appropriate in terms of entropy and the chaos has increased when NTP adosrbs on the surface of fullerene [15].

The negative values of adsorption enthalpy changes (ΔH_{ad}) showed the interaction process is exothermic [16]. Frontier molecular orbital (FMO) parameters including bandgap (Eg), chemical hardness (η), chemical potential (μ), electrophilicity (ω) and maximum transferred charge (ΔN_{max}) were also calculated and the results are given in Table 2. As can be seen, the bandgap value of fullerene increased significantly after NTP interaction from 1.950 (ev) to 7.730 (ev) for both studied conformers indicating the sharp alteration of electrical conductivity during the adsorption procedure. There, fullerene is an appropriate electrocatalytic sensing material for the development of new electrochemical sensors for the determination of NTP. The chemical hardness of NTP decline from 6.700 (eV) to 3.865 (eV) after interaction with fullerene indicating NTP-Fullerene complexes are more chemically reactive. The negative values of chemical potential for all of the structures showed all of the investigated structures are thermodynamically stable. The increasing of electrophilicity and maximum transferred charge of NTP after adsorption on the fullerene surface showed NTP-fullerene complexes are more electrophile than pure NTP without nanostructure.

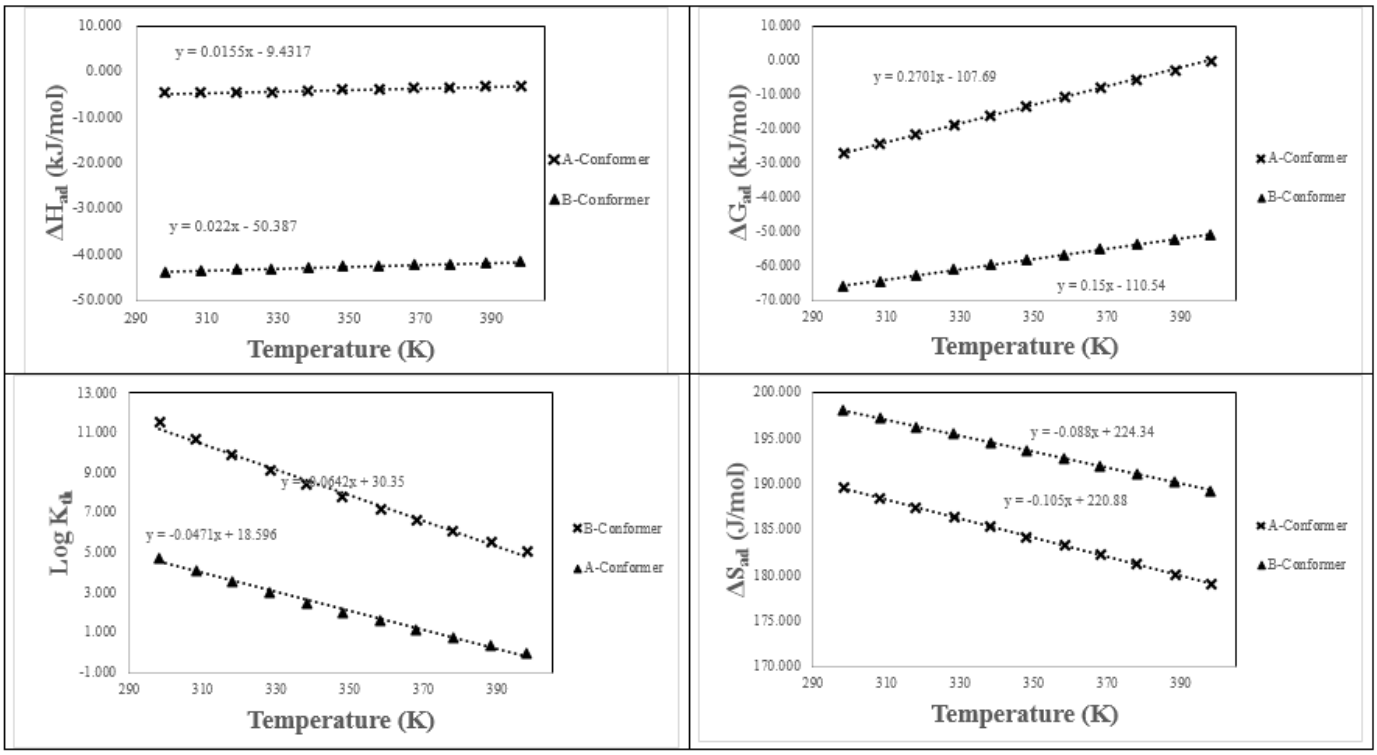

Figure 3. the values of ΔH_{ad} , ΔG_{ad}, the logatim of K_{th} and ΔS_{ad} as a function of temperature in the range of 298-398 K.

Table 2. The FMO parameters of NTP, C_{20} and their complexes

	E_{HOMO} (eV)	E_{LUMO} (eV)	E_g (eV)	$\%\Delta E_g$ (eV)	η (eV)	μ (eV)	ω (eV)	ΔN_{max} (eV)
NTP	-6.810	6.590	13.400	---	6.700	-0.110	0.001	0.016
C20	-5.060	-3.110	1.950	---	0.975	-4.085	8.558	4.190
A-Conformer	-4.440	3.290	7.730	296.410	3.865	-0.575	0.043	0.149
B-Conformer	-4.270	3.460	7.730	296.410	3.865	-0.405	0.021	0.105

Computational Details

The structures of Fullerene, NTP and their complexes were designed by Nanotube modeler 1.3.0.3 and GuassView 6 softwares [20, 21]. At the first step, the designed structures were optimized geometrically. Then, IR, NBO and FMO computations were implemented on them. All of the computations were performed by

Gaussian 16 software [22] by the density functional theory method in the B3LYP/6-31G (d) level of theory because in former studies about nanomaterials its results were in a good agreement with the experimental data. All of the calculations were implemented in the vacuum and in the temperature range of 298-398 at 10˚ intervals.

The studied processes were as follows:

NTP + Fullerene ⟶ NTP-Fullerene (1)

The values of adsorption energy values (E_{ad}) and thermodynamic parameters including adsorption enthalpy changes (ΔH_{ad}), Gibbs free energy changes (ΔG_{ad}), entropy changes (ΔS_{ad}), and thermodynamic equilibrium constants (K_{th}) were calculated by Equations 2-6 respectively.

$$E_{ad} = \left(E_{(\text{NTP-Fullerene})} - \left(E_{(\text{NTP})} + E_{(\text{Fullerene})} + E_{(\text{BSSE})}\right)\right) \quad (2)$$

$$\Delta H_{ad} = \left(H_{(\text{NTP-Fullerene})} - \left(H_{(\text{NTP})} + H_{(\text{Fullerene})}\right)\right) \quad (3)$$

$$\Delta G_{ad} = \left(G_{(\text{NTP-Fullerene})} - \left(G_{(\text{NTP})} + G_{(\text{Fullerene})}\right)\right) \quad (4)$$

$$\Delta S_{ad} = \left(S_{(\text{NTP-Fullerene})} - \left(S_{(\text{NTP})} + S_{(\text{Fullerene})}\right)\right) \quad (5)$$

$$K_{th} = \exp\left(-\frac{\Delta G_{ad}}{RT}\right) \quad (6)$$

In the referred equations, E is the total electronic energy of each structure, E_{BSSE} denotes the basis set superposition correction energy, H stands for enthalpy of the evaluated materials. The G denotes Gibbs free energy, S is the thermal correction of entropy, R is the ideal gas constants, T denotes the temperature [9-11].

Equations 7–12 were used to calculate the bandgap (E_g), chemical hardness (η), chemical potential (μ), maximum charge capacity (ΔN_{max}), and the electrophilicity (ω) of frontier molecular orbitals [32].

$$E_g = E_{LUMO} - E_{HOMO} \quad (7)$$

$$\%\Delta E_g = \frac{E_{g2} - E_{g1}}{Eg1} \times 100 \quad (8)$$

$$\eta = {}^{(E_{LUMO} - E_{HOMO})}/_{2} \quad (9)$$

$$\mu = {}^{(E_{LUMO} + E_{HOMO})}/_{2} \quad (10)$$

$$\omega = {}^{\mu^2}/_{2\eta} \quad (11)$$

$$\Delta N_{max} = -{}^{\mu}/_{\eta} \quad (12)$$

E_{LUMO} and E_{HOMO} in equation 6 are the energy of the lowest unoccupied molecular orbital and the energy of the highest occupied molecular orbital respectively. The E_{g1} and E_{g2} in Equation 7, are the bandgap of NTP-C_{20} complex and bandgap of C_{20} respectively [12-14].

Conclusion

NTP is a tricyclic antidepressant that is prescribed for the treatment of depression and anxiety disorders. This medicine has serious adverse side effects in high dosages and even can be lethal in the case of overdose. Therefore, NTP determination is very important. In this research, the performance of C_{20} as a novel sensing material for the construction of new electrochemical sensors to NTP measurement was evaluated by DFT computations. The values of adsorption energy and thermodynamic parameters showed NTP interaction with fullerene is exothermic, spontaneous and experimentally possible. The tangible increase of bandgap of fullerene in the adsorption process showed this nanostructure is a suitable sensing material for the electrochemical detection of NTP.

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