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Computational Studies and Energies for the Dioxa-Pentaazaheptacyclo-Hentriaconta-Octaen-One through Density Functional Theory and Natural Bond Orbital

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Abstract: In this paper, the molecular structure and electronic properties of 2,15-Dioxa-7,18,19,20,23-pentaazaheptacyclo [21.6.1.117,20.01,8.03,7.09,14.024,29]hentriaconta-9,11,13,17(31),18,24,26,28-octaen-30-one were calculated by the B3LYP density functional model using 6-31G, 6-311G, 6-311++G and 6-311++G(d,p) basis sets. B3LYP calculation results indicated some selected bond length and bond angle values for this molecule. The optimized geometries and frequencies of the stationary point and the minimum-energy of this structure were recognized. The obtained results were compared with the corresponding experimental data. Trustworthiness of this results is confirmed by good agreement with the experimental analyzes of this structure. The results obtained by different basis sets were compared and the necessity of correlation methods for studying these systems is discussed.

Keywords: Electronic structure, DFT (density functional theory) calculations, vibrational analysis, B3LYP level, NBO (natural bond orbital).

1. Introduction

The indole core structure is probably the most famous heterocycle and an important feature of a variety of natural products and pharmaceutical compounds [1]. Compounds include the indole moiety exhibit antibacterial and antifungal activities [2]. Furthermore, it has been reported that sharing of the indole 3-carbon atom in the formation of spiroindoline structures highly enhances biological activity [3-6]. The heterocyclic spirooxindole system is the core structure of many pharmacological agents and natural alkaloids [7-12]. For example, spirotryprostatin B, a natural alkaloid isolated from the fermentation broth of aspergillus fumigatus, has been identified as a novel inhibitor of microtubule assembly, and pteropodine and isopteropodine have been shown to modulate the function of muscarinic serotonin receptors. The interesting structural array and the highly pronounced pharmacological activity displayed by the class of spirooxindole compounds have made them attractive synthetic compounds [13-16]. Azaspiro derivatives are well-known [17-19], but the preparation of the corresponding oxa analogues has evolved at a relatively slow pace [20].

Pyrrole constitutes an important class of five-membered ring heterocycles with remarkable biological activities [21, 22], such as antitumour [23], analgesic [24, 25], antidepressant [26], antihistaminic [27], anti-inflammatory [28] and anti-parkinson [29, 30]. Furthermore, they are useful structures in the synthesis of natural products and heterocycles and are also widely used in material science. Consequently, the huge numbers of procedures have been developed for the construction of pyrroles in the literature. The well-known occurrence of substituted pyrrole shape

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amongst biologically important natural products and pharmaceuticals has stimulated great interest in its synthetic methods [31].

Oxazoles continue to hold a center stage in organic synthesis, although the structure of the first oxazole was reported over a century ago [32]. The field of oxazoles is extensive and includes natural products, medicinal chemistry, and materials science. The chemistry of oxazoles continues to be an important focus of academic and industrial laboratories around the world. Indeed, this heterocycle has elicited extraordinary creativity from medicinal and process chemists, polymer chemists, materials scientists, photographic dye chemists, and natural products chemists engaged in basic and applied research. Oxazoles are readily prepared from cyclic precursors to a remarkable variety of heterocyclic ring systems via various organic reactions, providing a stimulus for the creativity of synthethic chemists around the world [33, 34].

Direct quantum chemical computation of a molecular enthalpy of formation from the atomization energies requires the high-accuracy energy methods. Because of their computational expense, these methods can be applied now only to small structures. To make accurate predictions of thermo chemical data for larger molecules, composite methods have been developed over the past two decades. Among the widely used and successful composite methods are the Gn (Gaussian-n) family methods [35]. Ab initio DFT computations have recently become an efficient tool in the prediction of molecular structure, harmonic force fields, vibrational wave numbers, and IR (infrared) and Raman activities [36]. In last decade, the charge delocalization patterns and the chemical property of polyatomic molecules have been focused extensively. The information about the charge delocalization and the chemical reactivity is being helpful to the drug designers to design new type of pharmaceutical compounds. The NBO (natural bond orbital) is an effective method for the elucidation of residual resonance delocalization effects of the molecule and it also illustrates the deciphering of the molecular wave function in terms of Lewis structures, charge, bond order, bond type, hybridization, resonance, donor-acceptor interactions, etc. [37]. Therefore, the NBO analysis of important pharmaceutical compounds has been performed by various spectroscopists [38-41].

Most works dealing with interactions refer only to experimental or to theoretical studies. Recent advances in molecular modeling and in experimental techniques allow the direct observation of molecular structures and leads to an interpretation of physicochemical properties of solutions from the standpoint of microscopic details. Hence, during this study we report the optimized geometries, assignments and electronic structure calculations for an interesting heterocyclic compound. The structure of this compound has been optimized by using the DFT (B3LYP) method with various basis sets, using the Gaussian program. The comparison between theory and experiment is made.

2. Computational Details

All calculations were carried out using the computer program GAUSSIAN 09 [42]. The calculations of systems contain C, H, O and N are described by the standard 6-311++G(d,p) basis set. Vibrational analysis was performed at each stationary point, which confirmed its identity as a minimum energy. The population analysis have also been performed by the NBO method at B3LYP/6-311G level of theory using NBO under Gaussian 2009 program package. We calculated different parameter of molecule with several basis sets as candidates for our studies: 6-31G, 6-311++G, 6-311++G(d,p) and LANL2DZ. All calculations were restricted so that the spin states were pure and did not contain any spin contamination. The program Gaussian 09/DFT was employed to fully optimize the geometries without any symmetry limitations at the RHF (Restricted Hartree-Fock) with the standard basis sets, 6-31G, 6-311++G, LANL2DZ, 6-311++G(d,p) [43].

3. Results and Discussion

3.1 Molecular Properties

The structure of title compound is shown in Fig. 1. The calculated bond lengths and bond angles are listed in Tables 1 and 2.

We could compare the calculation results given in bond lengths and bond angle values with the experimental data because the crystal structure of the title compound was reported by Dasararaju Gayathrid [44]. From the theoretical values of both the Hartree-Fock and DFT/6-311G++(d,p) for this structure, we find that most of the optimized bond lengths and bond angles are slightly smaller, as well as longer than the experimental (X-ray data) values. This is due to the fact that the theoretical calculations are done on isolated molecule in gaseous phase and experimental results are done on molecule in solid phase. The correlations between the experimental and calculated geometric parameters obtained by several methods are shown in Tables 1 and 2. In our calculations, HF method correlates well for the bond lengths when compared with other methods (Shown in Table 1). Also, the B3LYP leads to geometric parameters of bond angles which are much closer to experimental data (shown in Table 2). As a result, the optimized bond lengths obtained by HF method and bond angles by DFT (B3LYP) method are in good agreement with the experimental values.

3.2 NBO (Natural Bond Orbital) Study on Structure

NBO Calculated Hybridizations are significant parameters for our investigation. The natural atomic

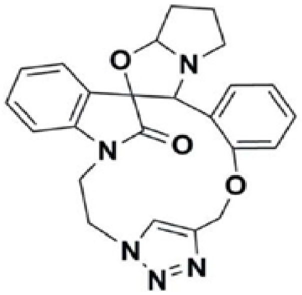

Fig. 1 The structure of Dioxa-pentaazaheptacyclo-hentriaconta-octaenone.

Table 1 The theoretical bond lengths (Å) of title molecule calculated by the DFT/B3LYP method with various basis sets.

Bond	6-31G	6-311G	LANL2DZ	6-311++G	6-311++G(d,p)	HF/6-311G	Experimental data (CIF) [28]
N33-N34	1.389	1.386	1.397	1.384	1.350	1.341	1.341(2)
N34-N35	1.323	1.327	1.334	1.328	1.298	1.285	1.31(3)
O13-C52	1.539	1.542	1.548	1.544	1.486	1.479	1.427(2)
C15-C11	1.648	1.641	1.653	1.639	1.631	1.599	1.538(2)
C11-O13	1.441	1.444	1.447	1.444	1.407	1.419	1.429(2)
C11-C54	1.539	1.537	1.551	1.540	1.551	1.526	1.541(2)
N10-C54	1.403	1.401	1.408	1.400	1.396	1.379	1.366(2)
N14-C52	1.442	1.442	1.448	1.448	1.438	1.440	1.482(2)
N14-C15	1.460	1.460	1.466	1.462	1.453	1.457	1.485(2)

Table 2 Angle amounts obtained by method DFT/B3LYP and a various basic sets.

Angle	6-31G	6-311G	LANL2DZ	6-311++G	6-311++G(d,p)	HF/6-311G	Experimental data (CIF)
N33-N34-N35	106.7	106.5	106.6	106.7	107.67	107.90	107.1(2)
N10-C41-C38	117.4	117.4	117.3	117.5	117.71	117.67	113.0(1)
C19-O37-C46	118.7	118.9	118.8	119.0	118.46	120.50	116.7(1)
C15-C11-C54	115.0	115.3	115.2	115.3	115.35	116.12	114.5(1)
O13-C11-C12	114.6	114.4	114.5	114.5	115.28	114.20	114.0(1)
O13-C52-C49	110.1	110.2	110.3	110.5	110.82	111.37	111.9(1)
C30-N14-C15	126.7	126.8	126.5	126.4	124.63	126.17	112.3(1)
O13-C52-N14	105.2	105.0	105.3	105.0	106.33	104.76	106.0(1)
O13-C11-C15	101.2	101.8	101.2	101.1	101.32	101.00	100.5(1)
C54-N10-C41	129.0	128.8	129.1	129.0	128.61	128.91	123.5(1)

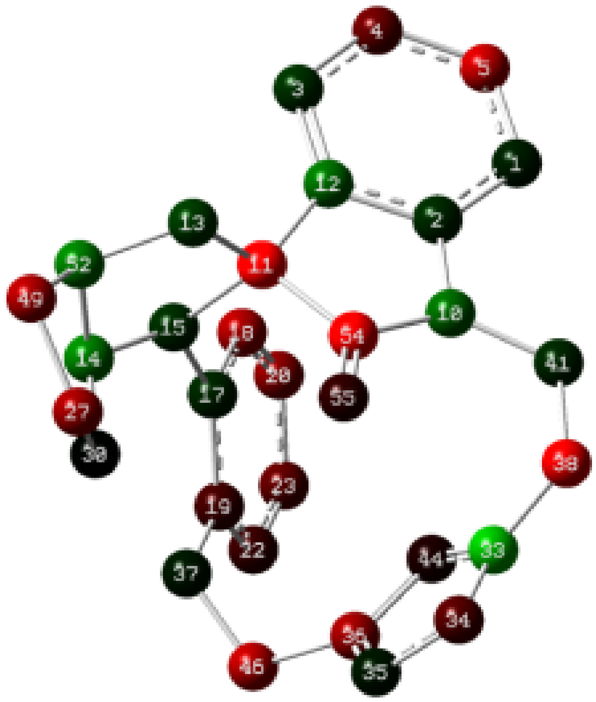

Fig. 2 Display charge distribution. (6-311++G(d,p)), Color range from -0.852 to +0.852.

charges of Dioxa-pentaazaheptacyclo-hentriaconta-octaen-one calculated by DFT methods using 6-311G basis set. These quantities are derived from the NBO population analysis. Density functional theory methods were employed to determine the optimized structure of title molecule. The NBO analysis of this spiroindoline structure have provided the detailed insight into the nature of electronic conjugation between the bonds in this molecule. Table 3 collects the natural charges on various atoms. The results show that the largest negative charges are located on tree atoms, O13, O37 and O55, also the largest positive charges are located on two atoms, C52 and C54.

The dipole moment (*μ*) is another property to obtain data on the electronic distribution in a molecule and is one of the properties used more conventionally to discuss and to rationalize the structure and reactivity of many chemical systems [45]. The results are shown in Table 4. Calculations of the HOMO (highest occupied molecular orbital)-LUMO (lowest unoccupied molecular orbital) gap (ΔE = ELUMO — EHOMO) [46] were done as well as the global hardness η that is approximated as ΔE/2, and can be defined under the principle of chemical hardness and softness (HSAB) [47]. Both parameters also provide information about the reactive behavior of molecules. Localization of the HOMO & LUMO orbitals are shown in Fig. 3. In Table 4, the calculated total energies, the energies for orbitals HOMO and LUMO, ΔE, η, and μ are reported for this structure.

The graphical illustration of the electrostatic potential surface for Dioxa-pentaazaheptacyclo-hentriaconta-octaenone is shown in Fig. 4. It is clear that there exists a small negative electrostatic potential cap at the triazole ring.

NBOs are localized few-center orbital's that describe the Lewis-like molecular bonding pattern of

Table 3 The calculated NBO atomic charges of title compound by the B3LYP method with 6-311G basis set.

Atom	N14	N10	N33	N34	N35	C46	C38	C36	C41	C54	C11	C15	C52	O55	O37	O13
Charges	-0.49837	-0.45972	-0.19670	-0.05322	-0.25379	-0.05365	-0.17808	0.04499	-0.18755	0.66468	0.19634	-0.00534	0.30150	-0.59827	-0.56141	-0.62266

Table 4 Molecular properties of compound calculated with B3LYP method and various basis sets.

Basis set	LUMO (eV)	HOMO (eV)	ΔE (eV)	Total energy (a.u.)	$\Delta E/2$	μ (debyes)
6-31G	-0.04482	-0.25072	0.20590	-1427.3	0.10295	7.065
6-311G	-0.05169	-0.25563	0.20367	-1427.6	0.10184	7.061
LANL2DZ	-0.04332	-0.21557	0.17225	-1427.5	0.08612	7.264
6-311++G	-0.05456	-0.25673	0.20217	-1427.6	0.10108	7.062
6-311++G (d,p)	-0.05438	-0.26431	0.20993	-1428.1	0.10496	6.220
HF/B3LYP/6-311G	0.09562	-0.32695	0.42257	-1418.6	0.21130	7.973

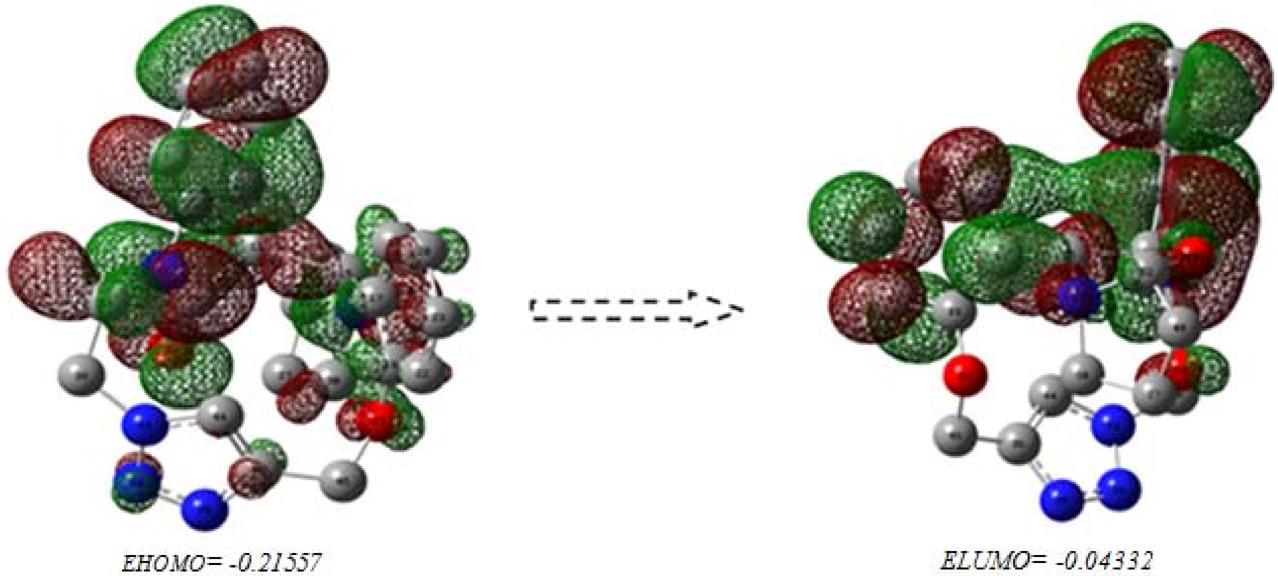

Fig. 3 Localization of the HOMO and LUMO orbitals by LANL2DZ.

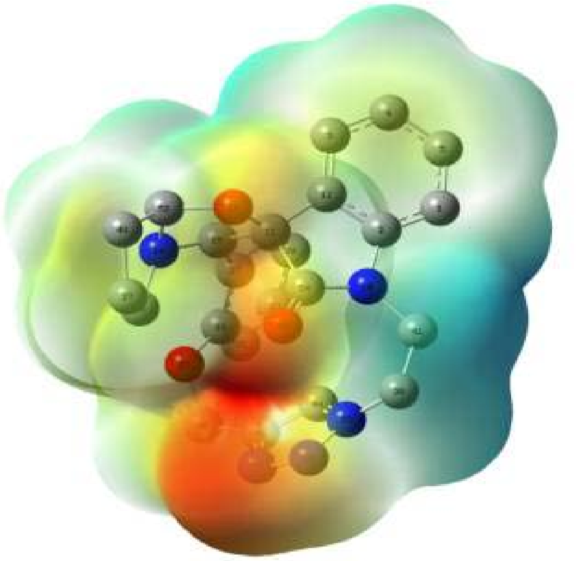

Fig. 4 Electron density from total SCF density (mapped with SCF). The electrostatic potential varies between -0.113 (red) and +0.113 (blue) a.u. (6-311 G).

electron pairs in optimally compact form. More precisely, NBOs are an ortho normal set of localized “maximum occupancy” orbital’s whose leading N/2 members (or N members in the open-shell case) give the most accurate possible Lewis-like description of the total N-electron density. This analysis is carried out by examining all possible interactions between “filled” (donor) Lewis-type NBOs and “empty” (acceptor) non-Lewis NBOs, and estimating their energetic importance by 2nd-order perturbation theory. Since these interactions lead to donation of occupancy from the localized NBOs of the idealized Lewis structure into the empty non-Lewis orbitals (and thus, to departures from the idealized Lewis structure description), they are referred to as “delocalization”

Table 5 Interactions between lone pairs and anti-bonding orbitals of the molecule, calculated by DFT/B3LYP method with 6-311G basis set.

Donor NBO (i)	Acceptor NBO (j)	E (kcal/mol)
LP (1) O 13	BD*(1) C 11 - C 15	3.1
	BD*(1) C 11 - C 12	4.5
	BD*(1) C 11 - C 54	7.4
	BD*(1) C 52 - H 53	4.0
LP (1) N 14	BD*(1) C 11 - C 15	9.7
	BD*(1) O 13 - C 52	13.6
	BD*(1) C 30 - H 31	4.8
	BD*(1) C 52 - H 53	4.4
LP (1) N 33	BD*(2) N 34 - N 35	38.0
	BD*(2) C 36 - C 44	34.8
	BD*(1) C 38 - H 40	5.5
LP (1) N 34	BD*(1) N 33 - C 44	6.1
	BD*(1) N 35 - C 36	6.9
LP (1) N 35	BD*(1) N 33 - N 34	9.6
	BD*(1) C 36 - C 44	5.4
LP (1) O 37	BD*(1) C 19 - C 22	5.8
	BD*(2) C 17 - C 19	16.9
	BD*(1) C 36 - C 46	4.6
LP (1) O 55	BD*(1) C 11 - C 54	3.2
LP (2) O 55	BD*(1) N 10 - C 54	26.5
	BD*(1) C 11 - C 54	18.5

Table 6 The NBO Calculated Hybridizations by (B3LYP/6-311G).

Bond	Hybridization
N 33 - N 34	$s^1p^{2.64}$, $s^1p^{3.70}$
N 34 - N 35	$s^1p^{2.57}$, $s^1p^{2.82}$
N 34 - N 35	$s^1p^{99.99}$, $s^1p^{99.99}$
N 35 - C 36	$s^1p^{1.96}$, $s^1p^{2.53}$
N 14 - C 52	$s^1p^{2.46}$, $s^1p^{2.97}$
O 13 - C 52	$s^1p^{3.41}$, $s^1p^{4.72}$
N 10 - C 54	$s^1p^{1.95}$, $s^1p^{2.30}$
C 11 - C 54	$s^1p^{2.88}$, $s^1p^{1.74}$
O 37 - C 46	$s^1p^{3.08}$, $s^1p^{4.22}$

corrections to the zeroth-order natural Lewis structure. NBO analysis and The NBO Calculated Hybridizations are summarized in Tables 5 and 6, respectively.

The IR spectroscopy of title compound was calculated by DFT/B3LYP presented in Fig. 6. As can be seen in this figure, there are good agreement with the experimental analyzes of IR spectrum and this structure.

The B3LYP leads to geometric parameters of bond angles which are much closer to experimental data. This pattern was not found for bond length as can be seen from Table 1. Theoretical calculation of bond and angle for the compound was determined by optimizing the geometry (Tables 1 and 2).

3.3 Frontier Molecular Orbital

HOMO and LUMO are the main orbital play in chemical stability [48]. The HOMO level represents the ability to electron donate donating, LUMO as an electron acceptor represents the ability to electron obtaining. The HOMO and LUMO energy were calculated by B3LYP/6-311G. This electronic absorption corresponds to the transition from the ground

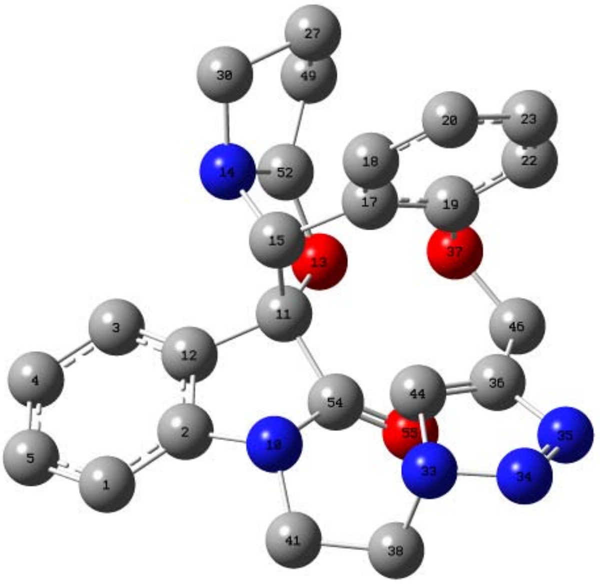

Fig. 5 The optimized equilibrium structure of title compound, and the numbering of atoms.

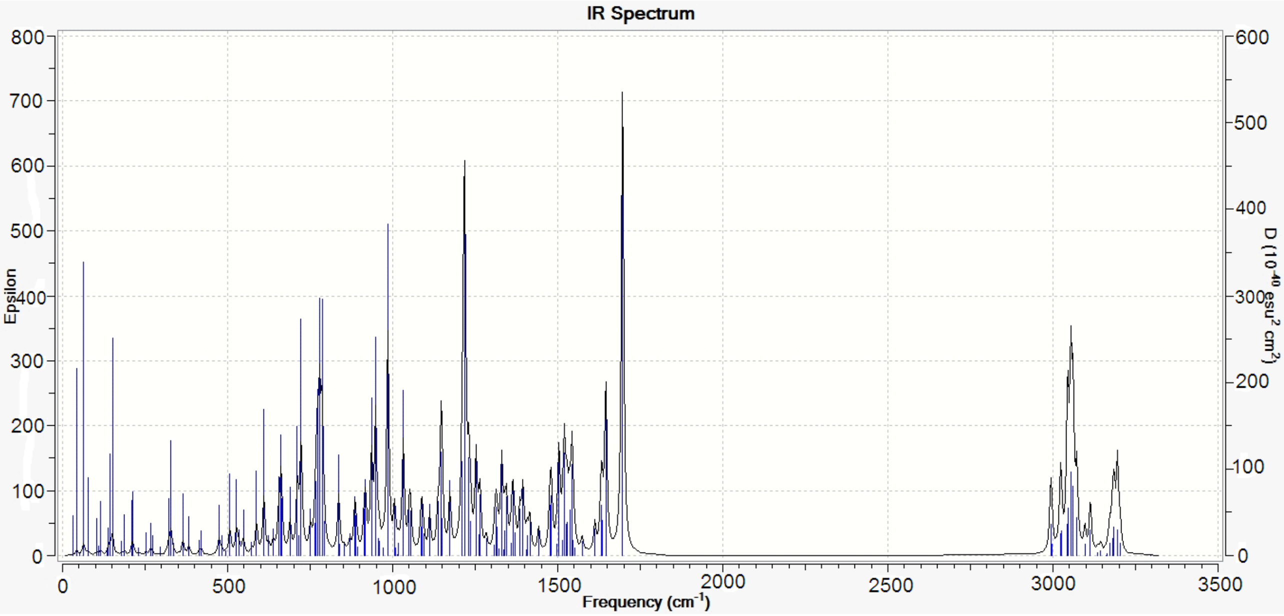

Fig. 6 The calculated IR spectrum of title structure.

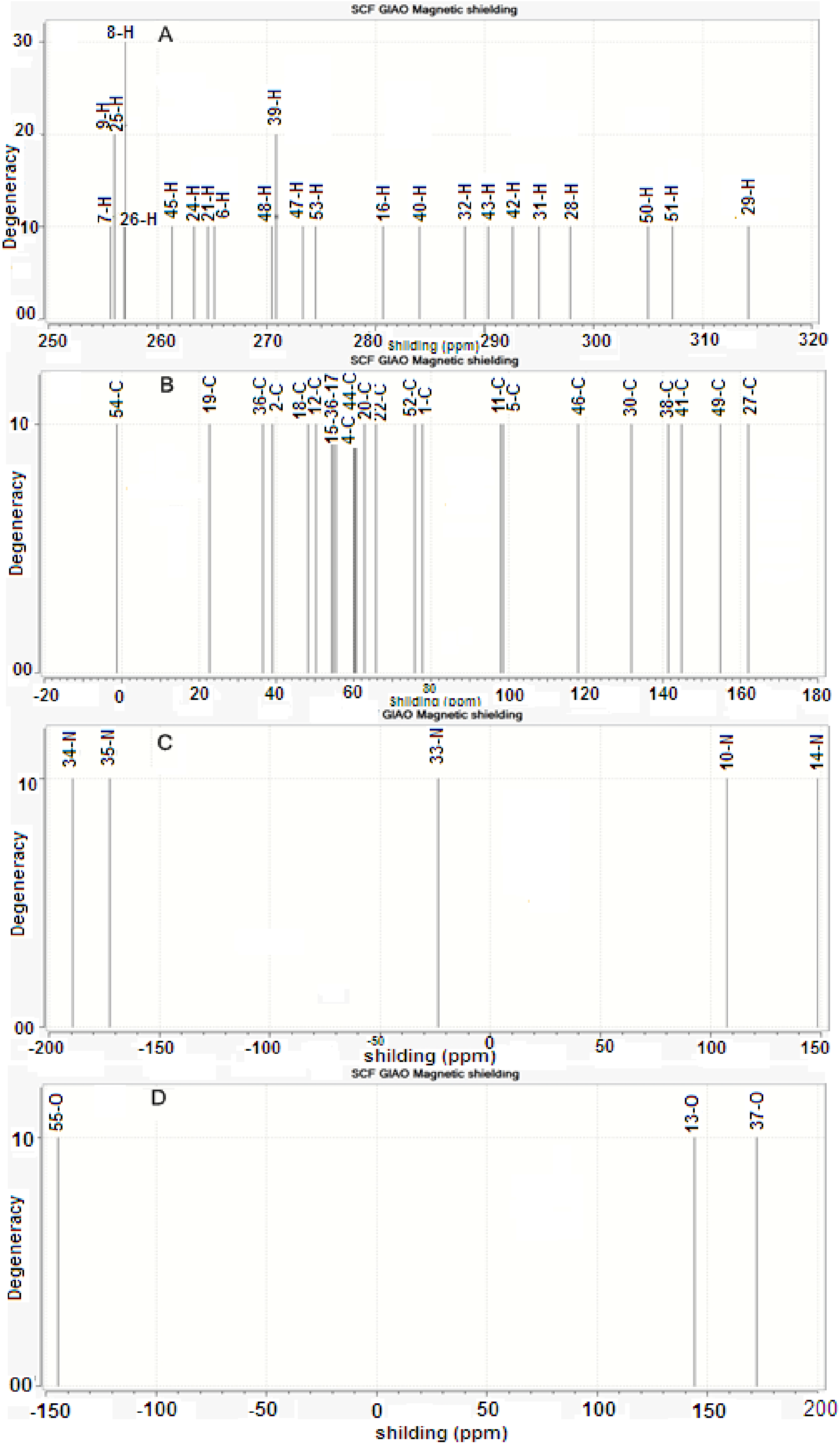

Fig. 7 Calculated various atoms NMR spectra for title molecule; ^{1}H-NMR (A), ^{13}C-NMR (B), ^{15}N-NMR (C), ^{17}O-NMR (D).

to the first excited state and is mainly described by one electron excitation from the LUMO level. Therefore, while the energy of the HOMO is directly related to the ionization potential, LUMO energy is directly related to the electron affinity. Energy difference between HOMO and LUMO orbital is called as energy gap that is an important stability for structures. In addition, 3D plots of HOMOs and LUMOs are shown in Fig. 3. The HOMO-LUMO energies were also calculated at the different basis sets and the values are listed in Table 4, respectively.

Finally, NMR (nuclear magnetic resonance) spectra of title molecule separately for each atom (N, H, C, and O) calculate by 6-311G basis set and presented in Fig. 7. As can be shown in these spectra, there are good agreement with the experimental analyzes of various atoms NMR spectra and this compound.

4. Conclusions

We have carried out density functional theory calculations on the structure and vibrational spectrum of 2,15-Dioxa-7,18,19,20,23-pentaazaheptacyclo [21.6.1.117,20.01,8.03,7.09,14.024,29]hentriaconta 9,11,13,17(31), 18,24, 26,28-octaen-30-one. The equilibrium geometry of molecule has been obtained as B3LYP levels of theory using the 6-311++G(d,p) basis set. We found that the HF method has performed better than DFT method for bond lengths. DFT method has performed better than HF method for bond angle. Also, the vibrational frequencies and NBO analysis by B3LYP method agree pleasurably with experimental results. On the basis of agreement between the calculated and experimental results, assignments of all the fundamental vibrational modes of molecule were examined and proposed in this investigation. Therefore, assignments made at higher level of theory with lower basis set with only reasonable deviations from the experimental values, seems to be correct. This study demonstrates that a scaled DFT/B3LYP calculation is powerful tool to understand the vibrational spectra of large-sized molecule. The group point of compound is C1.

Acknowledgements

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