



ISSN 0975-413X CODEN (USA): PCHHAX

Der Pharma Chemica, 2021, 13(11): 89-94
(<http://www.derpharmachemica.com/archive.html>)

Comparative study of ONA, PNA and PBA using Density functional techniques.

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ABSTRACT

This work presents the comparative study of o-nitroacetanilide (ONA), p-nitroacetanilide (PNA) and p-bromoacetanilide (PBA) by quantum chemical calculations and spectral techniques. The structural and spectroscopic data of the molecule were obtained from B3LYP/6-31 G (d,p) basis set calculations. The stability of molecule has been analyzed by NBO/NLMO analysis. Molecular electrostatic potential (MEP) at a point in space around a molecule gives an indication of the net electrostatic effect produced at that point by the total charge distribution of the molecule. The calculated HOMO and LUMO energy shows that charge transfer occurs within these molecules. Interpretation of atomic charges of the compounds helped to predict the electrophilic and nucleophilic reactions. Finally, the UV-Vis spectra and electronic absorption properties are explained and illustrated from the frontier molecular orbitals.

Keywords: PBA, PNA, ONA, NBO, NLMO, B3LYP.

INTRODUCTION

Aromatic compounds can easily be nitrated by the use of nitrating mixture, usually a mixture of concentrated nitric acid and sulphuric acid, results activating groups of ortho and para nitroacetanilide and a deactivating group of meta nitroacetanilide. Among this activated group o-nitroacetanilide is formed as a minor product whereas the latter forms as a major product. Acetamido group, being a bulky group, will cause the steric hindrance at the position of ortho, thus p-nitroacetanilide can be formed as a major product. Since o-nitroacetanilide is very much soluble in alcohol, it is very easy to isolate p-nitroacetanilide through crystallization. Benzene is mainly used as an intermediate to make other chemicals. P-bromoacetanilide (PBA) is belonging to the category of antipyretic and analgesic and used in the synthesis of organic compounds. It is used in the treatment of yeast anticancer drug and available in the trade name of antiseptin, asepsin, bromoantifebrin [1]. PBA and PNA is prepared by electrophilic substitution reaction. PBA and PNA were already reported by corresponding author.

MATERIALS AND METHODS

ONA and its derivatives were studied by several authors. The Study of intramolecular hydrogen bonding in ortho-substituted acetanilide compounds was reported by Seifollah Jalili et al. Hydrolysis of acetylthiocoline, o-nitroacetanilide and o-nitrotrifluoroacetanilide by fetal bovine serum acetylcholinesterase was studied by Mari'a F. Montenegro [2]. Crystal Structures and Density Functional Theory Calculations of O and P - Nitroaniline Derivatives: Combined Effect of Hydrogen Bonding and Aromatic Interactions on Dimerization Energy were carried out by Kaisa Helttunen. Hydrogen bond strengthening between o-nitroaniline and formaldehyde in electronic excited states: Theoretical studies were investigated by J Yang, A Y Li. Literature survey reveals that so far a comparative study for the title compounds has not yet been carried out

Hence, in this study, we set out experimental and theoretical investigation of the vibrational and electronic transitions of the compounds chosen. Theoretical geometrical parameters, UV spectra, HOMO and LUMO energies of molecules were calculated by using Gaussian 09W program at its ground state energy level [3]. The experimental spectrum (UV-Vis) was supported by the computed results, comparing with experimental characterization data, and absorption wavelength values are in fairly good agreement with the experimental results. The redistribution of Electron Density (ED) in various bonding, antibonding orbitals and E(2) energies have been calculated by Natural Bond Orbital (NBO) and natural localized molecular orbital (NLMO) analysis to give clear evidence of stabilization originating from the hyper conjugation of various intra-molecular interactions. The study of HOMO, LUMO analysis has been used to elucidate information regarding charge transfer within the molecule. Moreover, the Mulliken population analyses of the title compounds have been calculated and the calculated results are reported. The experimental and theoretical results supported each other, and the calculations are valuable for providing a reliable insight into the vibrational spectra and molecular properties [4].

Computational details

The computational studies of the title compounds PBA, PNA and ONA were done by using Gaussian 09W software package. The DFT calculations were performed by B3LYP 6-31G (d, p) level of theory by using Gaussian 09 programme. By combining the results of the GaussView 5.0 program with symmetry considerations, vibrational wavenumber assignments were made with a high extent of accuracy [5].

RESULTS AND DISCUSSION

Optimized molecular geometry

The optimized molecular geometry of PBA, PNA and ONA was calculated by DFT/B3LYP/6-31G (d, p) approach, in accordance with the labelling of atoms as shown in Figure 1. The optimized molecular geometry of PBA, PNA and ONA was presented in (Table 1).

Table 1: Selected optimized geometrical parameters of bond length (Å) of PBA, PNA and ONA

Bond length (Å)	PBA		PNA		ONA	
	Expt. ^(a)	B3LYP	Expt. ^(a)	B3LYP	Expt. ^(a)	B3LYP
C1-C2	1.53	1.52	1.5	1.52	1.5	1.51
C1-O3	1.22	1.22	1.2	1.21	1.2	1.22
C1-N4	1.37	1.33	1.36	1.38	1.36	1.38
N4-C5	1.44	1.4	1.34	1.4	1.34	1.38
C5-C6	1.41	1.4	1.33	1.4	1.33	1.42
C5-C10	1.37	1.4	1.33	1.4	1.33	1.41
C6-C7	1.39	1.39	1.33	1.38	1.33	1.4
C7-C8	1.39	1.39	1.33	1.39	1.33	1.38
C8-C9	1.37	1.39	1.33	1.39	1.33	1.4
C9-C10	1.39	1.39	1.33	1.39	1.33	1.38

And respectively. In the acetanilide group four types of prominent bond distances such as C-O, C-N, C-C and N-C, and six types of bond angles such as C-C-O, C-C-N, C-C-C, O-C-N, C-N-C and N-C-C, were identified and calculated.

NBO/NLMO analysis

NBO analysis is a useful method and emphasizes the role of intra- and inter-molecular interactions, interaction among bonds, conjugative interactions in the molecular systems. These interactions can be quantitatively described in terms of NBO approach which is expressed by means of second-order perturbation interaction energy, E(2). In Table 3, the perturbation energies of significant donor-acceptor interactions are presented. The larger the E(2) value, the intensive is the interaction between electron donors and electron acceptors.

Interactions of π -electrons in the rings give the greatest intramolecular hyperconjugative interaction energy and their values are C7-C8 \rightarrow N11-O12 (29.50 kcal/mol for PNA), C5-C10 \rightarrow C8-C9 (25.02 kcal/mol for PBA) and C5-C6 \rightarrow C9-C10 (98.93 kcal/mol for ONA). Hyperconjugative interactions of the σ - σ^* transitions are weak and their energies less than 15 kcal/mol. For a PBA molecule LP(1) N4 \rightarrow π^* (C1-O3) interaction gives a stabilization to the system by 58.68 kcal/mol, LP(3) (O13) \rightarrow π^* (N11-O12) interaction gives a strong stabilization to the system by 134.04

kcal/mol for ONA. In addition, the other important interaction of the LP (3) (O13)→ π^* (N11–O12) has the enormous stabilization energy of 161.04 kcal/mol for PNA. The natural localized molecular orbital (NLMO) analysis has been carried out since they show how bonding in a molecule is composed from orbitals localized on different atoms. The derivation of NLMOs from NBOs gives direct insight into the nature of the localized molecular orbital's "delocalization tails" (Table 2).

Table 2: Selected optimized geometrical parameters of Interaxial angles (°) of PBA, PNA and ONA

Interaxial angles (°)	PBA		PNA		ONA	
	Expt. ^(a)	B3LYP	Expt. ^(a)	B3LYP	Expt. ^(a)	B3LYP
C2-C1-O3	123.3	122.57	120	122.9	120	122.6
C2-C1-N4	117.7	113.51	120	113.4	120	112.7
O3-C1-N4	123.8	123.9	120	123.6	120	124.5
C1-N4-C5	128.9	129.03	120	129.1	120	129
N4-C5-C6	117.7	117.46	120	117.4	120	121.1
N4-C5-C10	123.8	123.32	120	123.2	120	121.9
C6-C5-C10	119.3	119.2	120	119.5	120	116.9
C5-C6-C7	120.7	120.92	120	120.7	120	121.2
C6-C7-C8	119.2	119.24	120	118.8	120	120.5
C7-C8-C9	120.1	120.58	120	121.3	120	118.9
C8-C9-C10	120.1	120.28	120	119.9	120	121.3
C5-C10-C9	119.2	119.75	120	119.5	120	121

Table 3: Shows significant NLMO's occupancy, percentage from parent NBO and atomic hybrid contributions of (PNA, PBA and ONA) calculated at the B3LYP level using 6-31G (d, p) basis set. The NLMO of third lone pair of oxygen atom O13 is the most delocalized NLMO and has only 95% contribution from the localized LP(3) O13 parent NBO, and the delocalization tail (~4%) consists of the hybrids of N11 and O12 for PNA molecule. Similarly, for ONA molecule the third lone pair of oxygen atom O13 has delocalization tail (~26%) consists of hybrids of N11 and O12. The stabilization energy of the molecule increases correspondingly the hybrid contribution atoms delocalization tail decreases.

Table 3: NBO/NLMO analysis

Interaxial angles (°)	PBA		PNA		ONA	
	Expt. ^(a)	B3LYP	Expt. ^(a)	B3LYP	Expt. ^(a)	B3LYP
C2-C1-O3	123.3	122.57	120	122.9	120	122.6
C2-C1-N4	117.7	113.51	120	113.4	120	112.7
O3-C1-N4	123.8	123.9	120	123.6	120	124.5
C1-N4-C5	128.9	129.03	120	129.1	120	129
N4-C5-C6	117.7	117.46	120	117.4	120	121.1
N4-C5-C10	123.8	123.32	120	123.2	120	121.9
C6-C5-C10	119.3	119.2	120	119.5	120	116.9
C5-C6-C7	120.7	120.92	120	120.7	120	121.2
C6-C7-C8	119.2	119.24	120	118.8	120	120.5
C7-C8-C9	120.1	120.58	120	121.3	120	118.9
C8-C9-C10	120.1	120.28	120	119.9	120	121.3
C5-C10-C9	119.2	119.75	120	119.5	120	121

a E(2) means energy of hyper conjugative interaction (stabilization energy)

Molecular electrostatic potential

MEP can be employed as an informative tool to describe different physical and chemical features, non-covalent interactions, proton affinities, solvation process and also in the evaluation of electrostatic charges for molecular mechanics and molecular dynamics studies. However, nucleophilic reaction happens more easily in the most negative area of MEP and electrophilic reaction happens more easily in the most positive area of the MEP. As evident from Fig. 2 of our study, electron densities are very low at the outer surface and near the hydrogen atoms (blue and light blue regions). Hence electrostatic potentials near these regions are positive. In the inner surface of the molecule (yellow and green regions), electron densities are on average high due to the presence of carbon atoms which has less electronegativity. Hence the electrostatic potential is less negative near these regions. The electron densities are very high at the centre and at one end of the molecule (red regions). This is due to the presence of strong electronegative atoms such as oxygen at terminal and nitrogen in the central linkage group. Thus,

the MEP map shows negative potential sites on oxygen and nitrogen atoms while positive potential sites are around the hydrogen atoms (Figure 2). Which is useful for the analysis of intermolecular potential between a pair of ONA, PBA and PNA molecules.

Interpretation on atomic charges

The atomic charges are important for the application of quantum mechanical calculations of the molecular system. Mulliken atomic charge calculations have a significant role in the application of quantum chemical calculations because, atomic charges affect the electronic structure, dipole moment, molecular polarizability and other properties of molecular systems. It is generally accepted that atomic charges yielded by Mulliken population are basis set dependent and their absolute magnitude have little physical meaning. The studied molecules PNA, PBA whose Mulliken atomic charges were compared with ONA, using the B3LYP method with 6-31G (d, p) basis set and the values are listed in (Table 4).

Table 4: Mulliken atomic charges of PNA, PBA and ONA

PNA		PBA		ONA	
Atoms	B3LYP	Atoms	B3LYP	Atoms	B3LYP
C1	0.57166	C1	0.56868	C1	0.57157
C2	-0.41283	C2	-0.41156	C2	-0.40771
O3	-0.4718	O3	-0.48294	O3	-0.47684
N4	-0.62018	N4	-0.61638	N4	-0.64027
C5	0.34136	C5	0.31888	C5	0.31998
C6	-0.14639	C6	-0.13191	C6	0.22885
C7	-0.09262	C7	-0.09332	C7	-0.10362
C8	0.24969	C8	0.05407	C8	-0.09384
C9	-0.10791	C9	-0.10678	C9	-0.08294
C10	-0.10583	C10	-0.09331	C10	-0.10728
N11	0.38077	Br11	-0.13597	N11	0.37676
O12	-0.40212	H12	0.15374	O12	-0.38888
O13	-0.40513	H13	0.14003	O13	-0.44217
H14	0.15829	H14	0.125	H14	0.14148
H15	0.14423	H15	0.26083	H15	0.15015
H16	0.12926	H16	0.08394	H16	0.14093
H17	0.26598	H17	0.10912	H17	0.30732
H18	0.09256	H18	0.11289	H18	0.14196
H19	0.13838	H19	0.14496	H19	0.10281
H20	0.14131			H20	0.10754
H21	0.1513			H21	0.15418

The results are plotted in Fig.3, although the molecules show similar charge pattern, but are with different magnitude. All the

carbons of the phenyl ring and with nitrogen (N4) and oxygen (O3, O12 and O13) are showing negative charges except the carbons (C1, C5 and C8) attached with nitrogen (N11) which are donor atoms. All hydrogen atoms in the compound are positively charged, which are acceptor atoms. According to Mulliken charge analysis, the substitution of Br, N, O, and CH3 group in compound combined by inducing carbon more acidic which leads more positive atomic charge (C1) on it. The magnitude of charge of hydrogen atoms which are present in CH3 group are tending to have same charge value. Mulliken charge analysis is a good way to account for differences in electronegativity of atoms within the molecule and frequently used for supporting the MEP results. MEP and Mulliken charge analysis can be used for interpreting and predicting the reactive behavior of a wide variety of chemical systems in both nucleophilic and electrophilic reactions. Carbon atoms of PBA, PNA and ONA (C1) has more positive charge (0.571a.u) than O3 (-0.482a.u).

Frontier molecular orbitals

The orbitals called HOMO and LUMO are the most important energy levels of a molecular system. These orbitals determine electron donating affinity and electron withdrawing affinity. The energy difference between these two orbitals have an important role in determining the molecular electrical transport properties. Therefore, it is largely responsible for determining chemical stability and spectroscopic properties of molecules. The HOMO and LUMO energy values were -6.00 and -0.56 eV for PBA, respectively, -6.74 and -2.28 eV for PNA while -6.63 and -2.68eV for ONA. The HOMO and LUMO energy values along with other parametric studies for PBA, PNA and ONA molecules are shown in (Table 5).

Table 5: UV-Vis absorption spectrum of PBA, PNA and ONA

States	PBA			PNA			ONA			
	Expt. λ obs	Gas Phase λ lcal	Ethanol λ lcal	Expt. λ obs	Gas Phase λ lcal	Ethanol λ lcal	Expt. λ obs	Gas Phase λ lcal	Ethanol λ lcal	Water λ lcal
S1	266	255.48	254.55	342	327.95	329.14	365	358.38	384.91	384.48
S2	246	241.57	246.41	282	298.57	314.26	302	326.27	326.69	326.33
S3	228	236.8	238.68	246	289.88	293.19	289	307.35	307.77	307.39

While examining $\Delta E = E_{LUMO} - E_{HOMO}$ energy intervals of the PBA, PNA and ONA, it is noticed that, for PBA structure it shows 5.43 eV, for PNA and ONA the values are 4.46 and 3.99 eV respectively. As a result, it is understood that the structure of PBA has most the stable state than the other two due to its larger energy difference.

UV-Visible spectral analysis

Ultraviolet spectra analysis of PBA, PNA and ONA has been investigated in gas phase and ethanol by theoretical calculations. On the basis of fully optimized ground-state structure, TD-DFT/B3LYP/6-31G(d, p) calculations have been used to determine the low lying excited states of PBA PNA and ONA. The theoretical absorption wavelengths and experimental values of PBA, PNA and ONA are listed in and its UV spectra are presented in Fig 4. Calculations of the molecular orbital geometry of PBA, PNA and ONA shows that its absorption maxima corresponds to the electron transition between frontier orbitals such as transition from HOMO to LUMO. As seen from (Table 6).

Table 6: Molecular properties of PBA, PNA and ONA

PBA		PNA		ONA	
Molecular properties	B3LYP	Molecular properties	B3LYP	Molecular properties	B3LYP
$E_{HOMO}(eV)$	-6.005	$E_{HOMO}(eV)$	-6.747	$E_{HOMO}(eV)$	-6.631
$E_{LUMO}(eV)$	-0.569	$E_{LUMO}(eV)$	-2.285	$E_{LUMO}(eV)$	-2.687
Orbital energy gap(eV)	5.436	Orbital energy gap(eV)	4.462	Orbital energy gap(eV)	3.994
Ionisation(I)	6.005	Ionisation(I)	6.747	Ionisation(I)	6.631
Electron affinity(A)	0.569	Electron affinity(A)	2.285	Electron affinity(A)	2.687
Global Hardness (h)	2.718	Global Hardness (h)	4.516	Global Hardness (h)	5.287
Global Softness(S)	0.367	Global Softness(S)	0.221	Global Softness(S)	0.189
Chemical Potential(m)	-3.287	Chemical Potential(m)	-2.231	Chemical Potential(m)	-4.659
Electronegativity(c)	3.287	Electronegativity(c)	2.231	Electronegativity(c)	4.659
Electrophilicity index(w)	5.403	Electrophilicity index(w)	4.978	Electrophilicity index(w)	10.85

The calculated absorption maxima values have been found to be 255.48, 254.55, 246.41, 241.57, 238.68 and 236.80 nm for PBA, 329.14, 327.95, 314.26, 298.57, 293.19 and 289.88 nm for PNA, 384.91, 358.38, 326.69, 326.27, 307.77 and 307.35 nm for ONA for all the three molecules in both gas and ethanol phase.

Global reactivity descriptors

The theory of FMO's is the ground for determining the other molecular properties and chemical quantities, such as ionization potential (I), electron affinity (A), global hardness (η), global softness (S), electronegativity (χ), chemical potential (μ) and electrophilicity (ω) which are also good indicators of the chemical stability of a molecule. The values of these parameters for the PNA, PBA and ONA molecule were estimated according to the expression given in the literature [4] and are reported in Table.6 and shown in Fig.5. The general rule derived from density functional theory is the electronic chemical potential must be constant everywhere in a chemical system at equilibrium. The hard state of a molecule may be due to its larger energy gap and the same way the soft state may be due to smaller energy gap value. The most stable structure has the largest HOMO-LUMO energy gap. According to Maximum Hardness Principle (MHP), the most stable structure should have maximum hardness value which being a minimum energy structure at constant chemical potential and hence the principle of maximum hardness has been proved in the present study. The calculated value of global softness of title compounds are found to be 0.367, 0.221 and 0.189 a.u., which describes the biological activity of the molecule.

CONCLUSION

Attempts have been made in the present work for the complete theoretical and experimental study of PBA, PNA and ONA, but with maximum priority to ONA molecule. The frontier molecular orbitals have been visualized and the HOMO-LUMO energy gap has been calculated. The stability and intramolecular interactions have been interpreted by NBO/NLMO analysis and the transactions give stabilization to the structure have been identified by second order perturbation energy calculations. The molecular orbitals, MESP surface drawn and the electronic transitions identified for UV-Vis spectra may lead to the understanding of properties and activity of PBA, PNA and ONA and the results will be of assistance in the quest of the experimental and theoretical evidence for the title molecules in reaction intermediates and pharmaceuticals. The Mulliken charges and natural atomic charges of the title molecules have been studied by DFT methods. The most stable structure should have maximum hardness value which being a minimum energy structure at constant chemical potential and hence the principle of maximum hardness has been proved in the present study.

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