Iranian Journal of Organic Chemistry Vol. 9, No. 4 (2017) 2205-2213

Investigation of intramolecular hydrogen bonding strength in dihydroxynaphthazarin: DFT and NBO studies

Mansoureh Zahedi-Tabrizi* and Nasim Shahmansoori

Department of Physics and Chemistry, Alzahra University, Tehran, Iran

Received: August 2017; Revised: September 2017; September: 2017

Abstract: In order to study hydrogen bond strength changes in Dihydroxynaphthazarin in comparison with Naphthazarin, the full geometry optimization of these molecules have been performed by Density Functional Theory (DFT) method, at B3LYP theoretical level, using 6-311++G** basis set. Also, ^{1}HNMR calculations were carried out by using GIAO methodand vibrational frequency calculations were performed for light and deuterated molecules.To support extracted results**,** NBO calculations(bond order, electron density, electron delocalization and steric effects) were also done at the same level of theory. In this study, we concluded that hydrogen bond strength in Dihydroxynaphthazarin is more than Naphthazarin when there is only one hydroxyl group in the vicinity of OH but when there is an OH group in the vicinity of carbonyl (even if there is another OH in the vicinity of hydroxyl groups) the related hydrogen bond strength is decreased.

Keywords: Dihydroxynaphthazarin, Naphthazarin, Density Functional Theory (DFT), NBO, Intermolecular hydrogen bonding.

Introduction

Investigation of hydrogen bonding has attracted significant attention over the years. 5,8-Dihydroxy-1,4-naphthoquinone, commonly known asNaphthazarin (NZ) is an interesting molecule from several points of view. It provides good models to investigate the nature of hydrogen bonds and the proton transfer reactions. It shows antimicrobial, cytotoxic, antiviral [1-5], anti-tumor [6-9] and antifungal [10] activities and its molecular structure are present in a number of molecules with important biological activity such as perylenequinones, alkannin, and shikonin. These are biological active pigments obtainable from natural sources [11].

The relative simplicity of the molecular structure of NZ together with its role as a model compound for biologically active molecules makes it an attractive target for both experimental and theoretical studies.

*Corresponding author. Tel.: +98 21 8569x2610; fax: +98 21 88041344; E-mail: zahedi@alzahra.ac.ir.

The structure of NZ has been the subject of many theoretical [12-14] and experimental studies such as neutron and X-ray diffraction [15-20], mass spectrometry [21], ^{1}H [22], ^{13}C [23-25], and ^{17}O [26] NMR, IR, and Raman [12,27-33] spectroscopy.The neutral form of NZ can exist in three different groups of symmetry (C_{2v}, C_{2h}, D_{2h}), The high-resolution IR and laser-induced fluorescence experiments led to the conclusion that main form of NZ has C_{2v} symmetry. This is in accordance with computational studies, so far realized only for gas phase, which unanimously prefers C_{2v} symmetry [13].

Currently, there is much interest in the study on hydroxylated naphthazarins because of their use in the development of cardioprotective preparations [34-36] and other applications [37-38]. 2, 3-dihydroxynaphthazarin (spinazarin) has been extracted, for the first time, from sea urchin scaphechinus mirabilis in small amounts. Natural products are often available in small amounts, which hinder the use of chemical methods in the establishment of their

structures since the available physiochemical methods do not allow unambiguous conclusions about the arrangement of the substitutes in the quinoid moiety. The known difficulties in the study of substituted hydroxyl naphthazarins are related to the question of prototropic tautomerism. Indeed, ^{1}H, ^{13}C, and ^{17}O NMR studies have shown that hydroxylated naphthazarins undergo rapid proton exchange between the α-hydroxyl and carbonyl groups giving rise to time-averaged spectra [39-41].IR-spectroscopy is definitely more rapid in comparison with NMR time scale and time averaging of the spectral parameters is not generally observed because the characteristic time of the IR method is shorter than the time of the vibrational transition [42].The effect of electron acceptor substitution (Cl) on the intramolecular hydrogen bond of NZ has been already reported [43].

According to difficulties encountered in experimental studies of these compounds and the importance of hydrogen bonding in determining the structure and behavior of these compounds, we have decided to study hydrogen bonding in dihydroxynaphthazarins by means of computational methods. Literature reveals that to the best of our knowledge DFT calculations of Dihydroxynaphthazarins(DNZ) have not been reported so far. Therefore, the present work deals with IR, NMR and NBO calculations, of DNZ and NZ to investigate hydrogen bond strength of DNZ in comparison with NZ, utilizing DFT (B3LYP) method with 6-311++G (d, p) as the basis set.

Results and discussion

Geometrical parameters:

Figure**1**. shows the numbering system and the structure of NZ and its hydroxyl substitutions. All molecules have been optimized at B3LYP level with 6-311++G(d,p) basis set that is shown in Figure **2**. The optimized geometry parameters of NZ and DNZs are summarized in Table **1**.

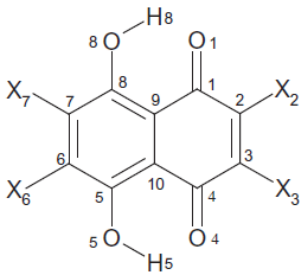
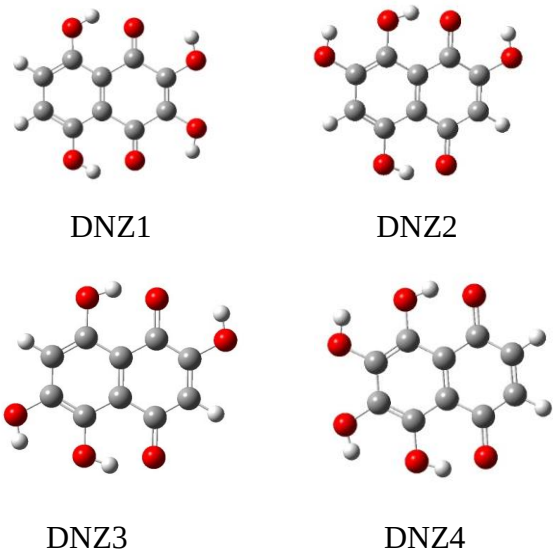


Figure 1: Numrering system and the structure of NZ and its hydroxyl substitutions.

NZ, X2, X3, X6, X7 = H. DNZ1, X2, X3 = OH, X6, X7 = H. DNZ2, X2, X7 = OH, X3, X6 = H. DNZ3, X2, X6 = OH, X3, X7 = H.DNZ4, X2, X3 = H, X6, X7 = OH. HNZ1, X3, X6, X7 = H, X2 = OH. HNZ2, X2, X3, X6 = H, X7 = OH.



According to the calculated results, in DNZ1, DNZ2 & DNZ3, presence of OH group in the neighborhood of carbonyl group decreases the O—H bond lengths and the O—H…O bond angles, and increases the O…O and O…H distances, which suggests weaker hydrogen bond in these compounds than that in NZ. On the other hand in DNZ2 & DNZ3 presence of these OH groups increase O4—H5 bond length and the O5—H5…O4 bond angles, and decreases the O4…O5 and O4…H5 distances which refers to stronger hydrogen bond. In DNZ4, O—H bond lengths increases, but O…O and O…H distances change slightly. This can be related to the opposite effects of OH groups. These groups have an electron donating effect in one side and on the other side is the formation of another hydrogen bond between H7and O8 or O5and H6.

Table 1: Some optimized parameters of optimized molecules

Bond Length (Å)	NZ	DNZ1	DNZ2	DNZ3	DNZ4
O1…O8	2.5890	2.6211	2.6242	2.6394	2.5910
O5…O4	2.5890	2.6211	2.5856	2.5603	2.5910
O1…H8	1.7069	1.7512	1.7649	1.7679	1.7073
O4…H5	1.7069	1.7511	1.6946	1.6696	1.7070
C1–O1	1.2421	1.2486	1.2453	1.2489	1.2443
C4–O4	1.2421	1.2486	1.2454	1.2462	1.2443
O8–H8	0.9893	0.9853	0.9856	0.9844	0.9934
O5–H5	0.9893	0.9853	0.9922	0.9981	0.9934
Bond Angle (°)					
O1…H8–O8	146.34	145.18	143.602	145.58	145.98
O4…H5–O5	146.34	145.19	147.265	146.27	145.98

NMR analysis:

The molecular structures of the titled molecules were optimized. Then, The absolute shielding for NZ, DNZs, and tetramethylsilane (TMS) have been obtained using the gauge-including atomic orbital (GIAO) method by using B3LYP functional with 6-311++G(d,p) basis set. The predicted ^{1}H chemical shifts are derived from equation $\delta = \sigma_0 - \sigma$, where δ is the chemical shift, σ is the absolute shielding, and σ_0 is the absolute shielding of TMS. The calculations were performed in the gas phase and the reported values are shown in Table **2**. In DNZ1 calculated chemical shifts of hydrogen have been reduced. The chemical shift of H8 in DNZ2 and DNZ3 is also less than NZ but H5 chemical shift in both of them is more than NZ. Finally, chemical shifts of hydrogen in DNZ4 are more than NZ.

NBO analysis:

NBO (Natural Bond Orbital) analysis provides an efficient method for studying intra and intermolecular bonding and the interactionamong bonds and also provides a convenient basis forinvestigation charge transfer or conjugative interactions in the molecularsystem [52].

Charge analysis:

The charge distribution calculated by the NBO method for the optimized geometries of NZ and DNZs are given in Table **3**. The natural charge on O1 atom in all of the molecules is more than NZ. This is because of electron donating effect of OH groups especially the ones near O1. The charge on O8 in DNZ1, DNZ2, and DNZ3 is less than NZ and in DNZ4 is more than NZ. Reduction of charge in DNZ1, DNZ2, and DNZ3 is because of less engagement of H8 with O1 (because O1 is engaged with H2) so the charge on O8 will reduce in comparison with NZ. The charge on O4 is increased in all of the molecules and thecharge on O5 is increased in DNZ2, DNZ3, and DNZ4 but decreased in DNZ1. The reason for this chargereduction, in this case, is the same as the reduction of charge on O8 in DNZ1, DNZ2, and DNZ3.These results are in good agreement with the calculated geometrical parameters results and the calculated chemical shifts of the hydroxylic proton for all molecules.

Table 2: Calculated hydrogen chemical shifts

	NZ	DNZ1	DNZ2(H5)	DNZ2(H8)	DNZ3(H5)	DNZ3(H8)	DNZ4
δ(ppm)	12.74	12.33	13.13	11.92	13.42	11.64	12.96

Table 3: Selected natural charges (e) for NZ and DNZs optimized at the B3LYP/6-311++G** level.

	Charge				
atom	DNZ1	DNZ2	DNZ3	DNZ4	NZ
C1	0.465	0.482	0.461	0.456	0.502
C8	0.397	0.346	0.425	0.325	0.391
C9	-0.196	-0.190	-0.230	-0.128	-0.193
O1	-0.649	-0.638	-0.651	-0.611	-0.601
O8	-0.656	-0.690	-0.653	-0.698	-0.660
H8	0.509	0.519	0.509	0.516	0.507
C4	0.477	0.503	0.513	0.456	0.502
C5	0.382	0.387	0.318	0.325	0.391
C10	-0.183	-0.203	-0.155	-0.128	-0.193
O4	-0.650	-0.615	-0.618	-0.611	-0.601
O5	-0.656	-0.661	-0.699	-0.698	-0.660
H5	0.509	0.508	0.519	0.516	0.507

Table 4: Comparison of selected Wiberg bond orders of NZ and DNZs.

	Bond order				
bond	DNZ1	DNZ2	DNZ3	DNZ4	NZ
C1–C9	1.1103	1.1242	1.1766	1.1274	1.1068
C8–C9	1.3428	1.3428	1.2759	1.3293	1.3318
C8–O8	1.1210	1.0798	1.1193	1.0964	1.1203
O1–C1	0.0267	1.5697	1.5396	1.5717	1.5986
O8–H8	0.6584	0.6557	0.6677	0.6259	0.6526
H8–O1	0.0689	0.0399	0.0591	0.0938	0.0769
C4–C10	0.0192	1.0997	1.0641	1.1270	1.1063
C5–C10	1.3418	1.3263	1.4049	1.3280	1.3307
C4–O4	1.5317	1.5692	1.5679	1.5716	1.5985
O4–H5	0.0686	0.0828	0.0933	0.0937	0.0768
O5–C5	1.1186	1.1244	1.0881	1.0936	1.1181
H5–O5	0.6580	0.6460	0.6244	0.6256	0.6522

Table 5: Selected second order perturbation energies(kcal/mol) E2 (donor–acceptor) for NZ and itshydroxylsubstitutions optimized at the B3LYP/6-311++G** level.

Donor	type	Accepter	type	NZ	DNZ1	DNZ2	DNZ3	DNZ4
C3-C4	σ	C4-O4	σ^*	0.97	0.66	1.19	1.11	1.25
C2-C3	σ	C4-O4	σ^*	2.06	1.54	0.55	2.35	2.36
C2-C3	π	C4-O4	π^*	19.26	23.64	5.44	25.80	21.05
C2-C3	π	C1-O1	π^*	19.26	23.63	19.93	17.33	15.75
O5-H5	σ	C5	RY*(1)	2.74	2.77	2.46	2.14	1.9
O8-H8	σ	C8	RY*(1)	2.63	2.73	2.04	2.75	3.03
O4	LP (1)	O5- H5	σ^*	2.85	3.34	3.05	3.42	3.43
O4	LP (1)	O3- H3	σ^*	-	0.6	-	-	-
O4	LP (2)	O5- H5	σ^*	19.10	16.23	20.74	23.28	23.43
O4	LP (2)	O3- H3	σ^*	-	2.87	-	-	-
O1	LP (1)	O2-H2	σ^*	-	0.6	0.52	0.71	-
O1	LP (2)	O2-H2	σ^*		2.86	2.62	3.43	
O1	LP (1)	O8- H8	σ^*	2.92	3.37	2.91	2.89	3.43
O1	LP (2)	O8- H8	σ^*	19.13	16.40	13.88	13.61	23.43
O8	LP (1)	O7- H7	σ^*	-	-	0.99	-	1.16
O5	LP (1)	O6- H6	σ^*	-	-	-	2.32	0.74

Table 6: Important pairwise steric exchange energies ΔE (*i*,*j*) (kcal/mol) interactions between NLMOs *i*,*j* for NZ and its hydroxyl substituents.

NLMO(i)	Type	NLMO(j)	Type	NZ	DNZ1	DNZ2	DNZ3	DNZ4
C3-O3	σ	C4-O4	σ	-	1.02	-	-	-
C5-O5	σ	C6-O6	σ	-	-	-	0.97	0.94
C6-O6	σ	C7-O7	σ	-	-	-	-	0.72
C7-O7	σ	C8-O8	σ	-	-	0.83	-	0.75
C6-O6	σ	O5	LP(1)	-	-	-		0.57
C3-O3	σ	O4	LP(2)	-	1.32	-	-	-
C4-O4	σ	O5-H5	σ	0.80	0.77	0.81	0.83	0.99
C4-O4	π	O3	LP(2)	-	1.34	-	-	-

C1-O1	σ	O8-H8	σ	0.80	0.85	0.73	0.79	0.99
C1-O1	π	O2	LP(2)	-	1.34	1.42	1.59	-
C2-O2	σ	O1	LP(2)	-	1.31	1.19	1.21	-
C5-O5	σ	C6-H6	σ	-	1.44	1.54	-	-
C1-O1	σ	C2-H2	σ	1.25	-	-	-	1.2
C4-O4	σ	C3-H3	σ	1.25	-	1.21	1.05	1.57
C8-O8	σ	C7-H7	σ	1.41	1.35	-	1.31	-
O5-H5	σ	O6	LP(1)	-	-	-	-	2.26
O6-H6	σ	O7	LP(1)	-	-	-	-	1.23
O7-H7	σ	O8	LP(1)	-	-	2.04	-	1.70
O5-H5	σ	O4	LP(1)	1.51	2.02	1.42	1.55	1.52
O5-H5	σ	O4	LP(2)	15.65	13.59	16.28	17.99	18.54
O8-H8	σ	O1	LP(1)	1.51	1.9	1.86	1.78	1.52
O8-H8	σ	O1	LP(2)	15.65	13.64	12.10	11.74	18.54
O2-H2	σ	O1	LP(1)	-	0.98	0.84	0.97	-
O2-H2	σ	O1	LP(2)	-	4.03	3.87	4.60	-
O3-H3	σ	O2	LP(1)	-	1.07	-	-	-
O3-H3	σ	O2	LP(2)	-	4.02	-	-	-
O2	LP(2)	O3	LP(2)	-	0.93	-	-	-

Bond orders

The calculated Wiberg bond orders for NZ and its hydroxyl substituted derivatives are collected in Table **4**.This table shows that the O…H bond order in NZ with the substitution of OH in the vicinity of carbonyl groups is less than that in NZ, which suggests weaker hydrogen bond in these compounds than that in NZ. However, the O…H bond order in NZ by substitution of OH near the hydroxyl groups is more than that in NZ, which suggests stronger hydrogen bond in these compounds than in NZ. It is noteworthy that in the molecules with two OH, one near the carbonyl group and one near the hydroxyl group, the effect of OH which is near carbonyl group is more than the other one.

Electron delocalization:

The second order Fock matrix was carried out to evaluate donor (i)–acceptor (j) interaction in the NBO analysis [53]. The result of the interaction is a loss of Lewis structure into an empty non-Lewis orbital. For each donor NBO (*i*) and acceptor NBO (*j*), the stabilization energy *E(2)* associated with delocalization ("2e-stabilization") $i \rightarrow j$ is estimated as

$$E(2) = \Delta E_{ij} = q_i \frac{F(i,j)^2}{\varepsilon_j - \varepsilon_i}$$

where q_i is the donor orbital occupancy, ε_i, ε_j are diagonal elements (orbital energies) and *F(i,j)*is the off-diagonal NBO Fock matrix element. Delocalization of electron density between occupied Lewis-type (bond or lone pair) NBO orbitals and formally unoccupied (anti-bond or Rydberg) non-Lewis NBO orbital corresponds to a stabilizing donor-acceptor interaction. The larger E(2) value, the more intensive is the interaction between electron donors and acceptor i.e. the more donation tendency from electron donors to electron acceptors and the greater the extent of conjugation of the whole system [54].The NBO analysis has demonstrated the charge transfer from the lone electron pair of proton acceptor (NY) is directed to the antibonding orbital of the proton donor (r*XAH). The increase of electron density in antibonding orbital weakens XAH bond, which leads to its elongation and concomitant lowering of the XAH stretch frequency. The stabilization energy (E(2)) due to NY and r*XAH interaction can reflect attractive interaction in H—Y bonding. So it offers us a theoretical approach to characterizing H-bond strength.

From the NBO study, we state that the atom having the lone pair of electrons transfer higher energy to its acceptors. Some of the E (2) values and types of the transitions are shown in Table **5**. According to this table, there is the significant difference between the interaction energies of NZ and its hydroxyl substitutions. The interaction energy between LP (2) of O1 atom and the σ^* orbital of O8—H8 in DNZ1,

DNZ2 and DNZ3 are decreased in comparison with NZ but this interaction is increased in DNZ4. These results lead to weaker O1…H8 hydrogen bond in DNZ1, DNZ2 and DNZ3 but stronger O1…H8 hydrogen bond in DNZ4. Another interaction which is of great importance is LP (2) O4→ σ* (O5—H5). The E2 energy related to this interaction is decreased in DNZ1 and is increased in DNZ2, DNZ3, and DNZ4. These changes refer to weaker and stronger O4…H5 hydrogen bond respectively.

Steric effect:

The qualitative concept of ‘‘steric repulsion’’ iscommonly used in chemistry, but the quantitative abinitio characterization of this concept is still incomplete. From the theoretical standpoint, steric repulsions arisefrom Pauli's exclusion principle and can be viewed asthe ‘‘quantum pressure’’ that resists crowding too manyelectrons into the same special region. In the natural stericanalysis, the steric repulsions are formulated in terms ofthe energy difference between filled NBOs and thecorresponding non-orthogonal ‘‘pre-NBOs’’ (PNBOs).It should be stressed that all occupied NLMOs makesignificant contributions to the total steric effect becauseall are involved in the mutual orthogonality associatedwith full N-electron antisymmetric state[55-56].

Some of the most important pairwise steric exchange energies, ΔE (i,j), interactions between NLMOs are summarized in Table **6**. Among these interactions, the interactions betweenσ O8—H8 and LP (2) O1 and σ O5—H5 and LP (2) O4, are the most important ones. As it is obvious from Table **6**, the interaction between σ O8—H8 and LP (2) O1 is decreased in DNZ1, DNZ2, and DNZ4 and is increased in DNZ3. Also the σ O5—H5 and LP (2) O4 interaction is increased in all of the molecules except DNZ1. These changes are in good agreement with the previous results. Considering these results, we concluded thatpresence of OH group in the neighborhood ofhydroxyl group makes the oxygen atoms come closer to each other, which results in the shorter O…O distance and strongerhydrogen bond.

Computational details

For meeting the requirements of both accuracy and computing economy, theoretical methods and basis sets should be considered. DFT has proved to be extremely useful in treating electronic structure of molecules. The density functional three-parameter hybrid model (DFT/B3LYP) [44-46] at 6-311++G (d,p) basis set level was adopted to calculate the properties of the molecules in this work. For hydrogen bonding, it is expected that both diffuse and polarization functions may be necessary for the basis sets. All the calculations were performed using the Gaussian 03w program package [47]. The geometry optimization of the structures, IR and NMR calculations have been carried out.The ^{1}H chemical shifts of NZ and its hydroxyl substituents have been achieved using the gauge-including atomic orbital (GIAO) method [48-50].To gain a more detailed insight into the nature of H-bond interaction, natural bond orbital (NBO) calculations have been applied using NBO5.0 program [51]. The results obtained at this level of theory were used for the interpretation of the hydrogen bond strength changes of DNZ in comparison with NZ.

Conclusion

The full geometry optimization of NZ and DNZs have been obtained from the DFT-B3LYPmethod using 6-311++G** basis set. Geometrical parameters along with proton chemical shift results support the results of NBO analysis. These results show that O1…H8 hydrogen bond strength is decreased in DNZ1, DNZ2, and DNZ3 and in DNZ4 is increased in comparison with NZ. Also, we concluded that O4…H5 hydrogen bond is increased in all of the molecules except DNZ1. All of the ^{1}HNMR chemical shift calculations are in agreement with these results.

Acknowledgments

The authors are grateful to Alzahra University for their supports to this research.

References

[1] Moir, M.; Thomson, R. H. *Phytochemistry*,**1973**, *12*, 1351.
[2] Ohta, A.; Sivalingham, P. M.; Lin, S.; Ikekawa, N.; Yaginuma, N.; Inada, Y. *Toxicon*, **1973**, *11*, 235.
[3] Remers, W.A.; *The Chemistry of Antitumour Antibiotics*, Wiley, New York, **1981**.
[4] Brinkworth, R.I.; Fairlie, D.P. *Biochim. Biophys. Acta.* **1995**,*1253*, 5.
[5] Park, B.; Lee, H.; Lee, S.; Piao, X.; Takeoka, G.R.; Wong, R.Y. ; Ahn, Y.; Kim, J. *J. Ethnopharm.***2006**,105 , 62.
[6] Rao, G.M.; Lown, J.W.; Plambeck, J.A. *J. Electrochem. Soc.***1978**,125 ,534.
[7] Rao, G.M.; Lown, J.W.; Plambeck, J.A. *J. Electrochem. Soc.***1978**,125 ,540.

[8] Crawford, P.W; Carlos, E.; Ellegood, J.C.; Cheng, C.C.; Dong, Q. ; Liu, D.f. ; Luo, Y.L. *Electrochim. Acta*. **1996**, 41, 2399.
[9] Ashnagar, A.; Bruce, J.M.; Dutton, P.L.; Prince, R.C. *Biochim. Biophys. Acta*,**1984**, 801 ,351.
[10] Meazza, G.; Dayan, F.E.; Wedge, D.E. *J. Agric. Food Chem.***2003**,51, 3824.
[11] Wiess, U.; Merlini, L.; Nasini, G. *Prog. Chem. Org. Nat. Prod.***1987**,52 , 1.
[12] Schutte, C. J. H.; Paul, S.O.; Smit, R. *J. Mol. Struct*. **1993**,*297*,235.
[13] Mariam, Y. H.;Musin,R. N. *THEOCHEM*, **2001**,*549*, 123.
[14] Mariam, Y.H.; Chantranupong, L. *J. Mol. Struct*. **2000**, *529*, 83.
[15] Herbstein, F. H.; Kapon, M.; Reisner, G.M.; Lehman, M. S.; Kress, R. B.; Wilson, R. B.; Shiau, W.I.; Duesler, E.N.; Paul, L. C.; Curtin, D.Y. *Proc. Roy. Soc. Lond*. A **985**, *399*, 295.
[16] Cradwick, P. D.; Hall, D.; Wood, M. K. *Acta Crystallogr*. *Sect*. *B***1971**, *B 27*, 1990.
[17] Rodriguez, J. G.; Cano, F. H.; Garcia-Blanko, S. *Acta Crystallogr. Sect*. *B***1977**, *B 33*, 491.
[18] Pascard-Billy, P.C. *Acta Crystallogr*. **1962** ,*15*, 519.
[19] Pascard-Billy, P.C. *Bull. Soc. Chim. Fr.***1962**, 2282.
[20] Pascard-Billy, P.C. *Bull. Soc. Chim. Fr.***1962**, 2293.
[21] W.G.; Stensen, E. Jensen, *J. Mass Spectrom*. **1995**, *30*, 1126.
[22] Mazzini, S.; Merlini, L.; Mondelli, R.; Nasini, G.; Ragg, E.; Scaglioni, L. *J. Chem. Soc. Perkin Trans. II* **1997**, 2013.
[23] Olivieri, A.; Paul, I. C.; Curtin, D. Y. *Magn. Reson. Chem*. **1990**,*28*, 119.
[24] Shea, K. J.; Beauchamp, P. S.; Lind, R.S. *J. Am. Chem. Soc.***1980**, *102*, 4544.
[25] Kobayashi, M.; Terui, Y.; Tori, K.; Tsuji, N. *Tetrahedron Lett*. **1976**,*8*, 619.
[26] Chandrasekaran, S.; Wilson, W.D.; Boykin, D.W. *Org. Mag. Res.***1984**, *22*, 757.
[27] Hadži, D.; Sheppard, N. *Trans. Faraday Soc.***1954**,*50*, 911.
[28] Bratan, S.; Strohbusch, F. *J. Mol. Struct*. **1980**, *61*, 409.
[29] Rentzepis, P.M.; Bondybey, V. E. *J. Chem. Phys*. **1984**,*80*, 4727.
[30] Bondybey, V.E.; Milton, S. V.; English, J. H.; Rentzepis, P.M. *Chem. Phys. Lett*. **1983**, *97*, 130.
[31] Paul, S.O.; Shutte, C.J.H.; Hendra, P. J. *Spectrochim. Acta.***1990**,*46A*, 323.
[32] Fabriciova, G.; Garc´ıa-Ramos, J. V.; Miskovsky, P.; Sanchez-Cortes, S. *Vibrational Spectrosc*. **2002**, 30, 203.
[33] Ramondo, F.; Bencivenni, L. *Struct. Chem*. **1994**, *5*, 211.
[34] Anufriev, V.Ph.; Novikov, V. L.; Maximov, O.B.; Elyakov, G.B.; Levitsky, D.O.; Lebedev, A.V.; Sadretdinov, S.M.; Shvilkin, A.V.; Afonskaya, N.I.; Ruda, M.Ya.; Cherpachenko, N.M. *Bioorg. Med. Chem. Lett*. **1998**, *8*, 587.
[35] PCT Int. Appl. WO 9 107 958 1991, CA **1991**, 115, 127023.
[36] PCT Int. Appl. WO 9 108 189 1991, CA **1991**, 115, 182874.
[37] M. Service, A. C. Wardlaw, Comp. Biochem. Physiol. 79 (1984) 161.
[38] Patent 2, GBR 159 056 1985, CA **1986**, 104, 83795.
[39] Moore, R. E.; Scheuer, P. J. *J. Org. Chem*. **1966**,*31*, 3272.
[40] Shiau, W. I.; Duessler, E. N.; Paul, E. C.; Curtin, D. Y. *J. Am. Chem. Soc.* **1980**,102 ,4546.
[41] Chandrasekaran, S.; Wilson, W. D.; Boykin, D. W. *Org. Magn. Reson.***1984**,22, 757.
[42] Gunter, H.; *NMR Spectroscopy, An Introduction*, Wiley: Chichester New York **1980** p: 315.
[43]] Zahedi-Tabrizi, M.; Farahati, R. *Comp. Theor. Chem.*, **2011**, 977, 195.
[44] Becke, A.D. *J. Chem. Phys.***1993**, *98*, 5648.
[45] Becke, A.D. *Phys. Rev*. **1988**,*A 38*, 3098.
[46] Lee, C.; Yang, W.; Parr, R.G. *Phys. Rev*. **1988**, *B 37* 785.
[47] Gaussian 03, Revision B.05, Frisch, M.J.; Trucks, G.W.; Schlegel, H.B.; Scuseria, G.E.; Robb, M.A.; Cheeseman, J.R.; Montgomery J.A.; Vreven, Jr., T Kudin, K.N.; Burant, J.C.; Millam, J.M.; Iyengar, S.S.; Tomasi, J.; Barone, V.; Mennucci, Cossi, B.M.; Scalmani, G.; Rega, N.; Petersson, G.A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, Nakajima, M.T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J.E.; Hratchian, H.P.; Cross, J.B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R.E.; Yazyev, O.; Austin, A.J.; Cammi, R. Pomelli, C.; Ochterski, J.W.; Ayala, P.Y.; Morokuma, K.; Voth, G.A.; Salvador, P.; Dannenberg, J.J.; Zakrzewski, V.G.; Dapprich, S.; Daniels, A.D.; Strain, M.C.; Farkas, O.; Malick, D.K.; Rabuck, A.D.; Raghavachari, K. Foresman, J.B.; Ortiz, J.V.; Cui, Q.

Baboul, A.G.; Clifford, S.; Cioslowski, J.; Stefanov, B.B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R.L.; Fox, D.J.; Keith, T.; Al-Laham, M.A.; Peng, C.Y.; Nanayakkara, A.; Challacombe, M.; Gill, P.M.W.; Johnson, B.; Chen, W.; Wong, M.W.; Gonzalez, C. Pople, J.A.; Gaussian 03, Revision D.01, Gaussian, Inc., Wallingford CT, **2004**.

[48]] Dodds, J.L.; McWeeny, R.; Sadlej, A.J. *Mol. Phys*. **1980**, *41*, 1419.

[49] McWeeny, R. *Phys. Rev*. **1962**,*126*, 1028.

[50] Wolinski, K.; Hilton, J.F.; Pulay, P., *J. Am. Chem. Soc*. **1990**, *112*, 8251.

[51] Glendening, E.D.; Badenhoop, J.K.; Reed, A.E.; Carpenter, J.E.; Bohmann, J.A.; Morales, C.M.; Weinhold, F. Theoretical Chemistry Institute, University of Wisconsin, Madison, WI, **001**. hhttp://www.chem.wisc.edu/~nbo5i.

[52] Snehalatha, M.; Ravikumar, C.; Joe, I.H.; Sekar, N.; Jayakumar, V.S. *Spectrochim. Acta. A***2009**,72 , 654.

[53] Szafran, M.; Komasa, A.; Adamska, E.B. *J. Mol. Struct.***2007**,827 , 101.

[54] Sebastian, S.; Sundaraganesan, N. *Spectrochim. Acta*. **2010**,75A, 941.

[55] Badenhoop, J.K.; Weinhold, F. *J. Chem. Phys*. **1997**,*107*, 5406.

[56] Badenhoop, J.K.; Weinhold, F. *Int.J. Quantum Chem*. **1999**,*72*, 269.