

The Conformational Effect of 6-Mono-Substituted and 6,7-Di-Substituted Derivatives of 5,6,7,8-Tetrahydrodibenzo[a,c]cyclo-octene on ^{13}C Chemical Shift

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ABSTRACT: Hartree-Fock (HF) and Density Functional Theory (DFT) methods employed to study the effect of conformational change on the ^{13}C chemical shifts of 6-mono axial and equatorial substituted and 6,7-di axial-axial, equatorial-equatorial and axial-equatorial substituted derivatives of 5,6,7,8-tetrahydrodibenzo[a,c]cyclo-octene. The geometry of the conformers have been optimized in the gas phase employing the 6-311G(d,p) basis set. The ^{13}C chemical shifts were calculated by Gauge Including Atomic Orbitals (GIAO) method. The correlation between calculated ^{13}C chemical shifts in the gas phase and experimental ones in CDCl_3 solvent is linear with squared regression coefficient of 0.96. Also the calculated ^{13}C chemical shift in the gas phase by the HF method shows better correlation with experimental ones compared with DFT method. Calculations of both the paramagnetic and diamagnetic shielding of carbon atoms demonstrate that the difference between experimental ^{13}C chemical shifts of the axial and equatorial substituted carbon atoms are more due to the paramagnetic than the diamagnetic shielding.

KEY WORDS: ^{13}C chemical shift, Diamagnetic shielding, Paramagnetic shielding, NMR, GIAO method, Conformation, Eight membered rings.

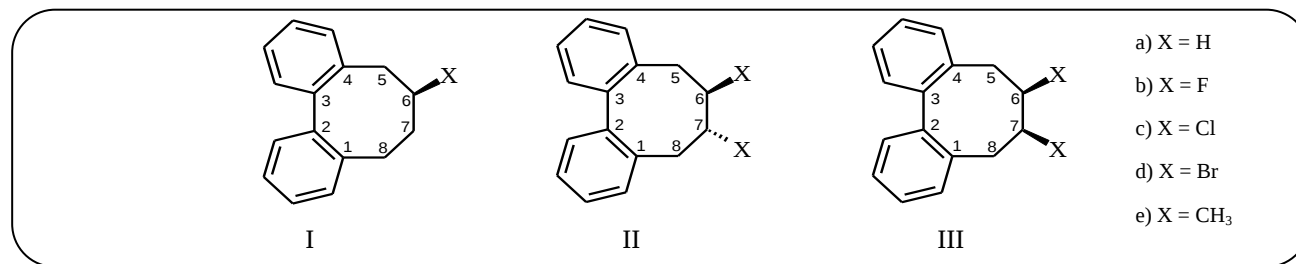
INTRODUCTION

Nuclear Magnetic Resonance (NMR) spectroscopy has become a powerful tool in chemistry and molecular biology [1-4]. There is no straightforward relationship between the structural properties of a molecule and the measured NMR signals, therefore, a reliable method to predict NMR chemical shifts is needed. *Ab initio* and DFT calculations could be used to calculate the NMR spectra [5].

Chemical shift is the most important parameters available in NMR. Both proton and ^{13}C chemical shifts provide chemists with a wealth of structural information. Many *ab initio* methods have been developed to predict the chemical shifts in terms of the chemical properties of atoms, by shielding tensor [6-20]. London's Gauge Including Atomic Orbitals (GIAO) was used by Ditchfield [6,7]

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Scheme 1: The 6-mono-substituted and 6,7-di-substituted derivatives of 5,6,7,8-tetrahydrido[1,2-b:4,5-b']diphenyl[8,7-c]octene.

to devise a method for calculating chemical shielding constant that has been demonstrated to be quite accurate and popular especially when was practically implemented in the context of highly correlated *ab initio* methods.

There have been many attempts for calculating the shielding constant σ , but none of the theoretical approaches has yielded exact values. If such calculations were possible, the spectrum could be exactly predicted. Theory and experiment lead to the conclusion that the reduction of the field, $\mathbf{B}$, and the associated resonance frequency is determined mainly by the distribution of the electron density in a molecule. The chemical shifts are therefore considerably affected by substituents which specifically influence the electron distribution.

The chemical shielding tensor can be identified as the second derivative of the energy with respect to the external magnetic field, $\mathbf{B}$, and the magnetic moment, $\mathbf{m}_j$, of nucleus j .

$$\sigma_{\alpha\beta,j} = \left(\frac{d^2 E}{dB_\alpha dm_{j,\beta}} \right)_{B_\alpha, m_{j,\beta}=0} \quad (1)$$

$$= \sum_{\mu\nu} P_{\mu\nu} \frac{\partial^2 h_{\mu\nu}}{\partial B_\alpha \partial m_{j,\beta}} + \sum_{\mu\nu} \frac{\partial P_{\mu\nu}}{\partial B_\alpha} \frac{\partial h_{\mu\nu}}{\partial m_{j,\beta}}$$

With $\alpha, \beta = d, y, z$. The following derivatives as the paramagnetic and diamagnetic component of the magnetic shielding tensor can be obtained [6,7,15,16].

$$\sigma_{\alpha\beta,j} = \sigma_{\alpha\beta,j}^d + \sigma_{\alpha\beta,j}^p \quad (2)$$

where

$$\sigma_{\alpha\beta,j}^d = \sum_{\mu\nu} P_{\mu\nu} \frac{\partial^2 h_{\mu\nu}^d}{\partial B_\alpha \partial m_{j,\beta}} \quad (3)$$

and

$$\sigma_{\alpha\beta,j}^p = \sum_{\mu\nu} P_{\mu\nu} \frac{\partial^2 h_{\mu\nu}^p}{\partial B_\alpha \partial m_{j,\beta}} + \sum_{\mu\nu} \frac{\partial P_{\mu\nu}}{\partial B_\alpha} \frac{\partial h_{\mu\nu}}{\partial m_{j,\beta}} \quad (4)$$

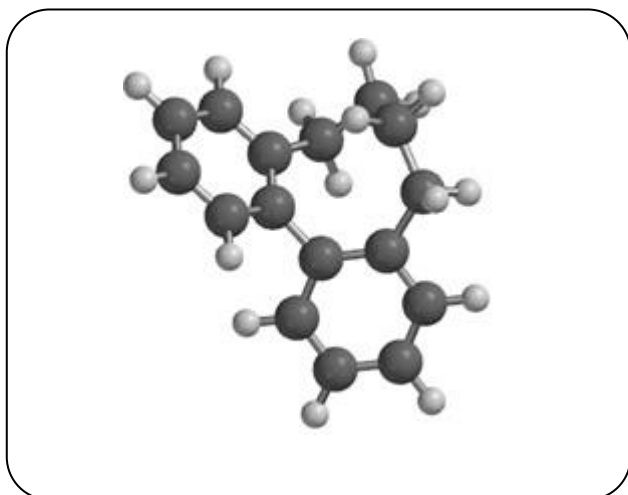
The σ^d and σ^p could be described as diamagnetic and paramagnetic contributions (Eq. (2)). σ^d is shown as unperturbed diamagnetic shielding contribution (Eq. 3), where σ^p involves both the unperturbed (first sentence) and the perturbed (second sentence) paramagnetic shielding contributions (Eq. (4)). In this article, we used the trace of the shielding tensors, since in many situations especially in the gas phase and in liquid environments it is adequate to compare the trace of tensors by experiment.

There were a few calculations on conformational dependence of ^{13}C chemical shifts, due to insufficient experimental data, so the important structural parameters, which affect the ^{13}C chemical shifts by conformational changes, have not been formulated yet.

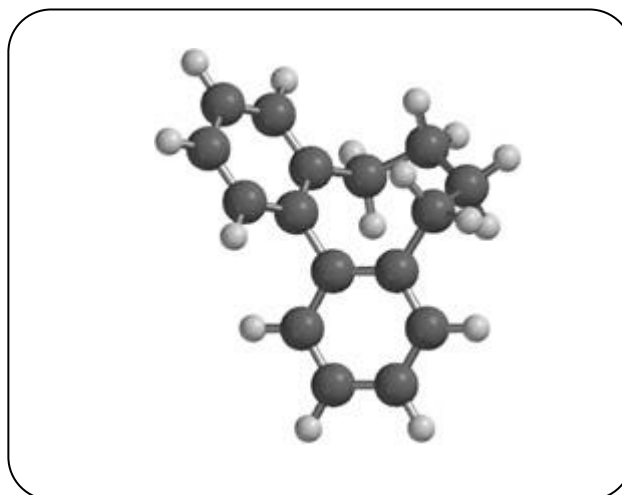
The 5,6,7,8-tetrahydrido[1,2-b:4,5-b']diphenyl[8,7-c]octene and their 6-mono-substituted and 6,7-di-substituted derivatives (Scheme 1) were studied by force field molecular mechanics and semiempirical calculations and by ^1H and ^{13}C NMR spectroscopy [21-24].

5,6,7,8-tetrahydrido[1,2-b:4,5-b']diphenyl[8,7-c]octene shows two local minimum energy conformations; Twist Boat (TB), and Twist Boat Chair (TBC) as the lower energy one (Schemes 2 and 3) [24].

The 6-mono-substituted and 6,7-di-substituted derivatives of 5,6,7,8-tetrahydrido[1,2-b:4,5-b']diphenyl[8,7-c]octene with hydrogen, fluorine (without experimental results), chlorine, bromine, and methyl substitution (Scheme 1) are used as the model compounds, which show conformational equilibrium in solution at room temperature [22,24]. Their ^{13}C NMR spectra [23] show that carbon atoms with *equatorial* substituent show higher chemical shift the *axial* ones (Table 3). In the present paper a correlation between calculated and experimental values of ^{13}C chemical shifts were obtained. Also the effect of neighboring atom as *axial* or *equatorial* substituent on the ^{13}C chemical shift are studied.



Scheme 2: Twist Boat (TB).



Scheme 3: Twist Boat Chair (TBC).

Computational details

The molecular geometry optimization of the TBC conformational forms of the 6-mono-substituted and 6,7-di-substituted derivatives of 5,6,7,8-tetrahydrotetrahydrodibenzo[a,c]cyclo-octene (Scheme 3) in the gas phase performed using Hartree-Fock (HF) as an all-electron linear combination of atomic orbitals and Density Functional Theory (DFT) calculations via the Spartan'10 computational package [25]. We used Becke's hybrid three-parameter exchange functional [26,27] and the correlation functional of the Lee, Yang, and Parr (B3LYP) method [28].

The basis set in our calculation combined with both HF and B3LYP methods is 6-311G(d,p). Vibrational frequencies have been calculated at the same level of theory for characterization of stationary points (no imaginary frequencies were observed).

Exact prediction of molecular response properties to external fields has notable significance in different areas of chemical physics. These especially refer to the second-order Nuclear Magnetic Response (NMR) properties, therefore techniques based on the magnetic resonance have gained fundamental significance in chemistry with one important parameter; isotropic (σ_{iso}) shielding. In the present paper, the ^{13}C shielding parameters calculations have been carried out on the basis of GIAO method at HF/6-311G(d,p) and B3LYP/6-311G(d,p) levels of theory using Spartan'10 computational package [20]. Tetra Methyl Silane (TMS) was assumed as the standard for calculating the chemical shifts from shielding isotropic values. Diamagnetic and paramagnetic shielding values were calculated to study their effects on ^{13}C chemical shift.

RESULTS AND DISCUSSION

The shielding parameters of 6,7,8, and 9 carbon atoms in the conformer of 6-mono-substituted and 6,7-di-substituted derivatives of 5,6,7,8-tetrahydrotetrahydrodibenzo[a,c]cyclo-octene (Scheme 1) are given in Table 1. These parameters are diamagnetic shielding (σ_{dia}), unperturbed paramagnetic shielding (σ_{para}), perturbed paramagnetic shielding (σ'_{para}), isotropic shielding (σ_{iso}), and chemical shift (δ).

We used isotropic shielding values of carbon atoms in TMS to calculate the chemical shifts. The relation between isotropic shielding and chemical shift is given by:

$$\delta = \sigma_{iso, \text{TMS}} - \sigma_{iso} \quad (5)$$

The calculated isotropic shielding values of carbon atoms of TMS in the gas phase at HF/6-311G(d,p) and B3LYP/6-311G(d,p) is given in Table 2. The experimental chemical shifts in CDCl_3 were taken from a previous work [23]. The experimental chemical shifts and the calculated one's are presented in Table 3.

In a molecule, shielding of an atom like carbon is greatly affected by the neighboring groups. The results showed that the chemical shifts in substituted carbon atoms in *equatorial* position are a few ppm more than the *axial* substituted carbon atoms; this could be attributed to the C-X bond length. The increasing of electronegativity in substitution atoms attracts the electron cloud of substituted carbon atoms, this leads to deshielding of carbon atoms and increasing in chemical shift value. However C-X distances

Table 1: ^{13}C shielding parameters of the 6-mono-substituted and 6,7-di-substituted derivatives of 5,6,7,8-tetrahydrodibenzo[a,c]cyclo-octene in HF and B3LYP method with 6-311G(d,p) basis set using GIAO approximation.

Molecule	Atom	HF/6-311G(d,p)					B3LYP/6-311G(d,p)					
		σ_{dia}	σ_{para}	σ'_{para}	σ_{iso}	δ	σ_{dia}	σ_{para}	σ'_{para}	σ_{iso}	σ_{aniso}	δ
Ia	C5	250.11	-10.86	-74.58	164.66	31.49	252.32	-7.39	-98.03	146.90	22.59	37.48
	C6	251.00	-11.64	-73.30	166.05	30.10	252.49	-11.12	-91.90	149.46	14.61	34.92
	C7	251.00	-11.64	-73.30	166.05	30.10	252.49	-11.13	-91.87	149.48	14.56	34.9
	C8	250.11	-10.86	-74.58	164.66	31.49	252.32	-7.39	-98.03	146.90	22.59	37.48
Ib, (a)	C5	250.49	-9.25	-80.22	161.02	35.14	253.00	-5.65	-104.31	143.03	25.16	41.35
	C6	248.48	-9.85	-121.65	116.98	79.17	250.44	-9.18	-150.84	90.43	80.28	93.95
	C7	251.26	-9.96	-81.56	159.74	36.41	252.82	-9.32	-100.74	142.76	19.57	41.62
	C8	249.87	-9.77	-70.63	169.48	26.68	252.17	-6.27	-93.55	152.35	31.95	32.03
Ib, (e)	C5	249.80	-10.39	-81.79	157.62	38.54	251.98	-7.26	-105.98	138.74	35.07	45.64
	C6	248.04	-0.21	-136.91	110.92	85.23	250.13	0.09	-166.44	83.78	78.50	100.6
	C7	250.69	-9.06	-80.67	160.96	35.19	252.21	-8.69	-99.18	144.34	23.71	40.04
	C8	250.23	-9.08	-72.18	168.97	27.19	252.59	-5.93	-95.05	151.60	27.28	32.77
Ic, (a)	C5	250.57	-11.25	-80.10	159.22	36.93	252.94	-7.92	-104.12	140.904	19.09	43.48
	C6	252.67	-15.56	-100.81	136.30	59.86	254.35	-14.35	-128.45	111.548	67.90	72.83
	C7	251.79	-10.96	-84.10	156.73	39.42	253.26	-10.20	-103.71	139.354	25.69	45.03
	C8	250.09	-10.36	-70.01	169.72	26.43	252.25	-6.91	-92.72	152.62	29.85	31.76
Ic, (e)	C5	250.60	-11.19	-84.28	155.13	41.02	252.87	-7.66	-109.06	136.15	42.22	48.23
	C6	252.15	-15.39	-104.04	132.71	63.45	253.80	-13.66	-131.95	108.19	61.20	76.19
	C7	251.62	-10.97	-83.78	156.87	39.28	253.13	-10.15	-103.02	139.96	32.94	44.42
	C8	250.26	-9.76	-74.18	166.32	29.84	252.50	-6.74	-97.46	148.29	23.78	36.09
Id, (a)	C5	250.44	-10.60	-81.47	158.37	37.79	252.83	-7.25	-105.87	139.71	17.82	44.67
	C6	252.37	-14.16	-102.61	135.59	60.56	253.87	-12.21	-130.70	110.96	77.04	73.42
	C7	251.75	-10.45	-85.54	155.75	40.40	253.23	-9.34	-105.90	138.00	28.63	46.38
	C8	250.13	-9.60	-71.17	169.37	26.79	252.31	-6.08	-94.23	152.00	29.02	32.38
Id, (e)	C5	250.49	-9.96	-86.17	154.37	41.79	252.73	-6.27	-111.26	135.21	45.28	49.17
	C6	252.04	-11.72	-106.95	133.36	62.79	253.50	-9.27	-134.26	109.97	67.54	74.41
	C7	251.54	-10.37	-85.27	155.91	40.25	253.04	-8.93	-105.44	138.67	36.66	45.71
	C8	250.28	-8.77	-76.16	165.34	30.81	252.52	-6.12	-99.28	147.12	22.71	37.26

Table 1: ^{13}C shielding parameters of the 6-mono-substituted and 6,7-di-substituted derivatives of 5,6,7,8-tetrahydrodibenzo[a.c]cyclo-octene in HF and B3LYP method with 6-311G(d,p) basis set using GIAO approximation (continued)

Molecule	Atom	HF/6-311G(d,p)					B3LYP/6-311G(d,p)				
		σ_{dia}	σ_{para}	σ'_{para}	σ_{iso}	δ	σ_{dia}	σ_{para}	σ'_{para}	σ_{iso}	δ
Ie, (a)	C5	250.08	-10.93	-78.68	160.46	35.69	252.32	-7.32	-103.26	141.75	42.63
	C6	250.71	-14.40	-68.92	167.39	28.76	252.01	-13.16	-90.30	148.54	35.84
	C7	251.63	-10.45	-81.11	160.07	36.09	252.80	-9.96	-100.31	142.53	41.84
	C8	250.19	-10.15	-71.28	168.75	27.40	252.43	-6.61	-93.92	151.89	32.49
Ie, (e)	C5	250.61	-9.90	-82.45	158.26	37.90	252.57	-6.42	-106.86	139.30	45.08
	C6	251.00	-11.43	-78.39	161.17	34.98	252.19	-9.00	-101.44	141.75	42.63
	C7	251.49	-10.45	-82.32	158.72	37.43	252.66	-9.86	-101.81	140.99	43.38
	C8	249.95	-10.04	-74.82	165.09	31.06	252.27	-6.52	-98.16	147.59	36.79
IIb, (a,a)	C5	250.26	-8.12	-77.60	164.53	31.62	252.82	-4.37	-101.20	147.26	37.12
	C6	248.79	-7.55	-125.70	115.54	80.61	250.87	-6.64	-154.64	89.59	94.79
	C7	248.79	-7.55	-125.69	115.55	80.61	250.87	-6.64	-154.64	89.59	94.79
	C8	250.26	-8.12	-77.60	164.53	31.62	252.82	-4.37	-101.20	147.26	37.12
IIb, (e,e)	C5	249.86	-8.66	-79.58	161.62	34.54	252.18	-5.57	-103.28	143.34	41.04
	C6	247.56	0.57	-139.05	109.08	87.08	249.68	0.99	-168.15	82.52	101.86
	C7	247.56	0.57	-139.05	109.08	87.08	249.68	0.98	-168.06	82.60	101.78
	C8	249.86	-8.66	-79.58	161.62	34.54	252.19	-5.56	-103.28	143.34	41.04
IIIb, (a,e)	C5	250.58	-7.58	-78.98	164.02	32.13	253.21	-4.04	-102.98	146.19	38.19
	C6	248.03	-8.23	-121.70	118.10	78.05	250.05	-7.62	-150.11	92.32	92.06
	C7	248.19	0.64	-139.21	109.62	86.53	250.30	1.45	-168.88	82.88	101.5
	C8	249.60	-9.53	-77.05	163.02	33.14	251.89	-6.25	-100.38	145.26	39.12
IIc, (a,a)	C5	250.49	-11.08	-75.04	164.37	31.78	252.80	-7.71	-98.26	146.84	37.54
	C6	253.46	-15.63	-104.65	133.19	62.96	255.10	-14.33	-131.96	108.81	75.57
	C7	253.46	-15.63	-104.65	133.19	62.96	255.10	-14.32	-131.96	108.82	75.56
	C8	250.49	-11.08	-75.04	164.37	31.78	252.80	-7.70	-98.27	146.84	37.54
IIc, (e,e)	C5	250.78	-10.87	-83.31	156.60	39.55	253.10	-7.57	-107.84	137.68	46.70
	C6	252.64	-15.87	-108.57	128.20	67.96	254.34	-13.85	-137.08	103.42	80.96
	C7	252.64	-15.87	-108.57	128.20	67.96	254.32	-13.79	-137.17	103.37	81.01
	C8	250.78	-10.87	-83.31	156.60	39.55	253.11	-7.45	-107.68	137.97	46.41
IIIc, (a,e)	C5	250.81	-10.23	-81.13	159.45	36.71	253.08	-7.27	-104.75	141.06	43.32
	C6	253.26	-14.55	-104.26	134.46	61.70	254.94	-13.12	-132.45	109.37	75.01
	C7	252.97	-14.36	-108.25	130.35	65.80	254.56	-12.48	-136.83	105.25	79.13
	C8	250.61	-11.01	-79.79	159.81	36.35	252.79	-7.51	-103.60	141.68	42.70

Table 1: ^{13}C shielding parameters of the 6-mono-substituted and 6,7-di-substituted derivatives of 5,6,7,8-tetrahydrodibenzo[a,c]cyclo-octene in HF and B3LYP method with 6-311G(d,p) basis set using GIAO approximation (continued).

Molecule	Atom	HF/6-311G(d,p)					B3LYP/6-311G(d,p)				
		σ_{dia}	σ_{para}	σ'_{para}	σ_{iso}	δ	σ_{dia}	σ_{para}	σ'_{para}	σ_{iso}	δ
IIId, (a,a)	C5	250.37	-9.95	-76.83	163.59	32.56	252.72	-6.51	-100.61	145.60	38.78
	C6	253.14	-13.41	-107.64	132.08	64.08	254.62	-11.28	-135.99	107.35	77.03
	C7	253.14	-13.41	-107.65	132.08	64.08	254.62	-11.29	-135.88	107.44	76.93
	C8	250.37	-9.95	-76.83	163.59	32.56	252.72	-6.51	-100.62	145.59	38.79
IIId, (e,e)	C5	250.70	-9.35	-86.28	155.06	41.09	253.02	-6.04	-111.25	135.73	48.65
	C6	252.41	-12.45	-111.62	128.33	67.82	253.90	-9.34	-141.10	103.46	80.92
	C7	252.41	-12.45	-111.62	128.33	67.82	253.90	-9.34	-141.10	103.46	80.92
	C8	250.70	-9.35	-86.28	155.06	41.09	253.02	-6.05	-111.24	135.73	48.65
IIId, (a,e)	C5	250.69	-9.05	-84.04	157.59	38.56	252.98	-6.25	-107.92	138.81	45.57
	C6	252.84	-12.97	-106.82	133.06	63.10	254.32	-10.66	-136.67	106.99	77.39
	C7	252.81	-11.37	-110.21	131.23	64.92	254.20	-8.80	-139.05	106.36	78.02
	C8	250.54	-9.72	-82.44	158.38	37.77	252.73	-5.96	-107.14	139.64	44.74
IIe, (a,a)	C5	250.04	-10.42	-75.21	164.40	31.75	252.36	-6.45	-98.99	146.92	37.46
	C6	251.67	-13.27	-76.76	161.64	34.52	252.52	-12.02	-98.61	141.89	42.49
	C7	251.67	-13.27	-76.76	161.64	34.52	252.52	-12.03	-98.67	141.81	42.57
	C8	250.04	-10.42	-75.21	164.40	31.75	252.34	-6.45	-99.09	146.80	37.58
IIe, (e,e)	C5	250.60	-9.47	-82.73	158.40	37.75	252.60	-5.78	-107.31	139.50	44.88
	C6	251.38	-11.37	-83.30	156.70	39.45	252.32	-8.70	-107.56	136.06	48.32
	C7	251.39	-11.37	-83.34	156.67	39.48	252.35	-8.68	-107.81	135.87	48.51
	C8	250.60	-9.47	-82.70	158.43	37.72	252.59	-5.90	-107.23	139.46	44.92
IIIe, (a,e)	C5	250.04	-10.04	-80.96	159.04	37.12	252.28	-6.49	-105.72	140.07	44.31
	C6	251.23	-12.55	-75.88	162.80	33.36	252.24	-11.51	-97.54	143.18	41.20
	C7	251.64	-10.06	-84.03	157.55	38.60	252.55	-7.50	-107.82	137.23	47.15
	C8	250.57	-9.48	-78.08	163.01	33.14	252.62	-5.94	-101.51	145.17	39.21

Table 2: ^{13}C Chemical shift of the tetra methyl silane in HF and B3LYP method with 6-311G(d,p) basis set using GIAO approximation.

	HF/6-311G(d,p) (gas)	B3LYP/6-311G(d,p) (gas)
σ_{iso}	196.15	184.38

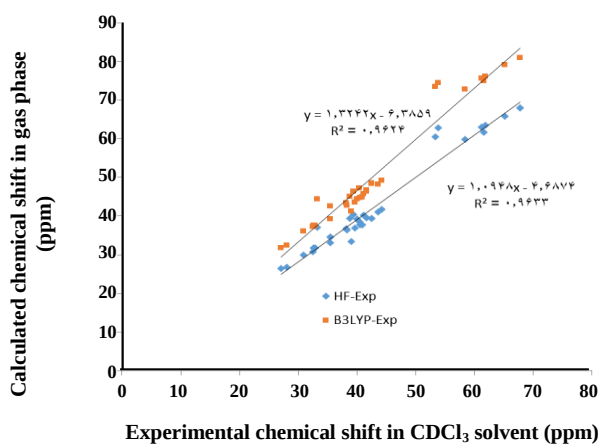


Fig. 1: The relationship between calculated chemical shift in gas phase and experimental one's in CDCl_3 solvent.

in *equatorial* conformers are relatively the same as *axial* conformers (Table 4). This confirms that the electronic environment of carbon atoms has not changed, so the diamagnetic shielding (σ_{dia}) of substituted carbon atoms has not changed. It is a well-known fact that the change in environment of carbon atoms is one of the most conclusive factors in variation of chemical shifts.

Studying both the paramagnetic and diamagnetic shielding of carbon atoms (Table 1) demonstrates that the difference between isotropic shielding values of the *axial* and *equatorial* substituted carbon atoms (C6 in 6-mono-substituted and C6 and C7 in 6,7-di-substituted derivatives of 5,6,7,8-tetrahydrodibenzo[a,c]cyclo-octene) is related to the paramagnetic shielding ($\sigma_{\text{para}} + \sigma'_{\text{para}}$) more than the diamagnetic shielding (σ_{dia}). Paramagnetic shielding ($\sigma_{\text{para}} + \sigma'_{\text{para}}$) is affected by electron currents induced by electric field due to interference effects of other atoms especially neighboring atoms. The *equatorial* substituted carbon atoms have higher negative paramagnetic shielding value than *axial* substituted carbon atoms. Also the difference between experimental ^{13}C chemical shift values of the *axial* and *equatorial* substituted carbon atoms (Table 3) show that the paramagnetic shielding

is affected on chemical shift more than the diamagnetic shielding.

The computed results in Table 3 in HF/6-311G(d,p) level of theory, show a better agreement with the experimental ones compared with B3LYP/6-311G(d,p) level of theory. The Root-Mean-Square Deviation (RMSD) of HF calculated chemical shifts with the experimental ones is 2.70 ppm, while the RMSD of B3LYP calculated chemical shifts with experimental ones is 9.00 ppm. The most prominent differences between the calculated and experimental results are obtained for 6-mono-Br substituted. These differences in HF method are 7.17 and 8.94 ppm and for B3LYP method are 20.03 and 20.56 ppm for *axial* and *equatorial* positions respectively.

The relationship between calculated chemical shift in gas phase and experimental ones in CDCl_3 solvent is linear with squared regression coefficient of 0.96 (Fig. 1). This suggests that the increase in theoretical and experimental chemical shift is quite applicable. Although, electron correlation effects in HF calculations are not checked such as B3LYP method [10,11], the calculated results that were obtained with HF method in gas phase are in greater conformity with the experimental results than B3LYP method.

CONCLUSIONS

The present work clarified conformational effect on the ^{13}C chemical shifts of 6-mono *axial* and *equatorial* substituted and 6,7-di *axial-axial* and *equatorial-equatorial* substituted derivatives of 5,6,7,8-tetrahydrodibenzo[a,c]cyclo-octene. In general, the carbon atoms with *equatorial* substitutions show chemical shifts down fields than the carbon atoms with *axial* substitutions. The contribution of paramagnetic and diamagnetic shielding of carbon atoms in isotropic shielding demonstrates that the difference between ^{13}C chemical shift values of the *axial* and *equatorial* substituted carbon atoms (as obtained experimentally or theoretically) is related to the paramagnetic shielding more than the diamagnetic shielding.

Table 3: ^{13}C Chemical shift of the 6-mono-substituted and 6,7-di-substituted derivatives of 5,6,7,8-tetrahydrodibenzo[a.c]cyclo-octene in HF and B3LYP method with 6-311G(d,p) basis set using GIAO approximation and experimental values of them

Molecule	Atom	HF/6-311G(d,p)	B3LYP/6-311G(d,p)	Experimental ⁱ	HF-Exp	B3LYP-Exp
Ic, (a)	C5	36.93	43.48	39.65	-2.72	3.83
	C6	59.86	72.83	58.43	1.43	14.4
	C7	39.42	45.03	38.73	0.69	6.30
	C8	26.43	31.76	27.07	-0.64	4.69
Ic, (e)	C5	41.02	48.23	43.54	-2.52	4.69
	C6	63.45	76.19	61.86	1.59	14.33
	C7	39.28	44.42	39.99	-0.71	4.43
	C8	29.84	36.09	30.93	-1.09	5.16
Id, (a)	C5	37.79	44.67	40.50	-2.71	4.17
	C6	60.56	73.42	53.39	7.17	20.03
	C7	40.40	46.38	39.44	0.96	6.94
	C8	26.79	32.38	28.04	-1.25	4.34
Id, (e)	C5	41.79	49.17	44.26	-2.47	4.91
	C6	62.79	74.41	53.85	8.94	20.56
	C7	40.25	45.71	41.12	-0.87	4.59
	C8	30.81	37.26	32.52	-1.71	4.74
IIc, (a,a)	C5	31.78	37.54	32.58	-0.80	4.96
	C6	62.96	75.57	61.29	1.67	14.28
	C7	62.96	75.56	61.29	1.67	14.27
	C8	31.78	37.54	32.58	-0.80	4.96
IIc, (e,e)	C5	39.55	46.70	41.64	-2.09	5.06
	C6	67.96	80.96	67.79	0.17	13.17
	C7	67.96	81.01	67.79	0.17	13.22
	C8	39.55	46.41	41.64	-2.09	4.77
IIc, (a,e)	C5	36.71	43.32	38.19	-1.48	5.13
	C6	61.70	75.01	61.54	0.16	13.47
	C7	65.80	79.13	65.16	0.64	13.97
	C8	36.35	42.70	38.29	-1.94	4.41
IIe, (a,a)	C5	31.75	37.46	32.89	-1.14	4.57
	C6	34.52	42.49	35.40	-0.88	7.09
	C7	34.52	42.57	35.40	-0.88	7.17
	C8	31.75	37.58	32.89	-1.14	4.69
IIe, (e,e)	C5	37.75	44.88	40.90	-3.15	3.98
	C6	39.45	48.32	42.51	-3.06	5.81
	C7	39.48	48.51	42.51	-3.03	6.00
	C8	37.72	44.92	40.90	-3.18	4.02
IIe, (a,e)	C5	37.12	44.31	33.23	3.89	11.08
	C6	33.36	41.20	39.05	-5.69	2.15
	C7	38.60	47.15	40.42	-1.82	6.73
	C8	33.14	39.21	35.40	-2.26	3.81

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Table 4: C-X distances in equatorial and axial conformers of the 6-mono-substituted and 6,7-di-substituted derivatives of 5,6,7,8-tetrahydridibenzo[a.c]cyclo-octene in HF and B3LYP method with 6-311G(d,p) basis set

Molecule	C-X bond	Bond length (Å)	
		RHF/6-311G(d,p)	B3LYP/6-311G(d,p)
Ib, (a)	C6-F	1.380	1.412
Ib, (e)	C6-F	1.382	1.413
Ic, (a)	C6-Cl	1.822	1.846
Ic, (e)	C6-Cl	1.825	1.848
Id, (a)	C6-Br	1.991	2.013
Id, (e)	C6-Br	1.993	2.014
Ie, (a)	C6-CH ₃	1.532	1.535
Ie, (e)	C6-CH ₃	1.532	1.536
IIb, (a,a)	C6-F	1.375	1.406
	C7-F	1.375	1.406
IIb, (e,e)	C6-F	1.376	1.406
	C7-F	1.376	1.406
IIIb, (a,e)	C6-F	1.369	1.400
	C7-F	1.374	1.403
IIc, (a,a)	C6-Cl	1.816	1.840
	C7-Cl	1.816	1.840
IIc, (e,e)	C6-Cl	1.815	1.837
	C7-Cl	1.815	1.837
IIIc, (a,e)	C6-Cl	1.803	1.826
	C7-Cl	1.809	1.833
IId, (a,a)	C6-Br	1.987	2.015
	C7-Br	1.987	2.014
IId, (e,e)	C6-Br	1.982	2.005
	C7-Br	1.982	2.004
IIId, (a,e)	C6-Br	1.969	1.993
	C7-Br	1.974	1.996
IIe, (a,a)	C6- CH ₃	1.533	1.536
	C7- CH ₃	1.533	1.536
IIe, (e,e)	C6- CH ₃	1.537	1.539
	C7- CH ₃	1.536	1.539
IIIe, (a,e)	C6- CH ₃	1.534	1.536
	C7- CH ₃	1.534	1.537

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