Journal of the Serbian Chemical Society
JSCS-info@shd.org.rs • www.shd.org.rs/JSCS

J. Serb. Chem. Soc. 76 (6) 879–890 (2011) UDC 665.344.2+547.521:539.125.4:519.677
JSCS–4168 *Original scientific paper*

A theoretical study of the intramolecular proton transfer and calculation of the nucleus independent chemical shift in juglone and some of its derivatives

ESMAIL VESSALLY[1], EHSAN FEREYDUNI[2]*, MAHDI KAMAEE[3]
and SHAHRAM MORADI[4]

[1]Payame Noor University (PNU), Zanjan, Iran, [2]Department of Chemistry, Tabriz Branch, Islamic Azad University, Tabriz, Iran, [3]Department of Chemistry, Shahid Chamran University, Ahvaz, Iran and [4]Faculty of Chemistry, Islamic Azad University, North Tehran Branch, Tehran, Iran

(Received 30 September 2010)

Abstract: In the present study, first, the intramolecular proton transfer (IPT) process of juglone and its derivatives were theoretically investigated in the gas phase and the effect of electron-withdrawing and electron-releasing substituents in different positions of the phenyl and benzoquinone rings of juglone on the IPT process was studied in which the geometries, energies and thermodynamic functions of the compounds were obtained using density functional theory (DFT) calculations at the B3LYP/6-31+G(2d,p) level. Next, the influence of IPT on changing the aromaticity of the phenyl and benzoquinone rings was investigated. To determine the aromaticity of the rings, nuclear independent chemical shift (*NICS*) values were calculated for the ground state and transition state structures (GS_1, TS and GS_2) using the continues set of gauge transformations (CSGT) procedure at the B3LYP/6-311+G(2d,p) level.

Keywords: juglone; *NICS*; aromaticity; intramolecular proton transfer; DFT.

INTRODUCTION

1,4-Naphthoquinones are widely distributed in plants, fungi and some animals[1] and many are found to exhibit an interesting range of pharmacological properties, including antibacterial,[2,3] antimicrobial,[4] antiviral,[5] trypanocidal,[6] anticancer,[7] antimalarial,[8,9] and antifungal[10] activities, especially when a hydroxyl group is present at the C5 position.[11] Juglone is a quinone produced in the roots, leaves and bark of walnut trees.[12,13] It contains an intramolecular hydrogen bond (IAHB) between hydroxyl and keto groups. The IAHB can be formed between donor and acceptor groups of the same molecule when the molecular configu-

---

* Corresponding author. E-mail: e_fereyduni@yahoo.com
doi: 10.2298/JSC100930080V

ration and conformation bring them within hydrogen bond geometry. Studies on IAHB became increasingly popular in the past[14,15] and hydrogen bonding complexes have been extensively studied with a wide range of experimental techniques and calculations.[16,17] One of the most significant structures capable of bearing hydrogen bond is the O–H···O unit which is studied in this paper. Sometimes, an IAHB decisively influences the stability of molecular conformations and favors tautomerization *via* an intramolecular proton transfer (IPT) process. In juglone as well, a hydrogen atom can transfer from hydroxyl to a keto group *via* the IPT process. IPT reactions are among the most important processes that occur in chemistry and biology.[18,19] Juglone is a natural ligand and many complexes can be formed *via* IPT reactions. Therefore juglone and its analogues can act as absorbent or carrier of metal ions and amino acids in biologic systems. Substituent effects are among the most important concepts of structural effects influencing the chemical, physico-chemical, and biochemical properties of chemical species.[20]

Juglone is an aromatic organic compound and aromaticity is one of the most characteristic phenomena associated strongly with a cyclic π-electron delocalization.[20] Aromaticity fundamentally characterizes the molecular structure, physical properties and chemical reactivity from both thermodynamic and kinetic standpoints,[21,22] which is used as a powerful predictive tool for compounds which had not been prepared previously. Aromaticity seems to be significant in any logical application of organic chemistry. However, a more detailed investigation of aromatic molecules requires a quantitative estimation of the degree of aromaticity of cyclic conjugated systems. There are several criteria used frequently for a compound to be considered aromatic, *i.e.*, stability of cyclic π-system, near planarity, bond length equalization, delocalized π-electrons satisfying the Hückel ($4n+2$) electron counting rule and unusual magnetic properties, such as magnetic susceptibilities.[23,24] π-Electron delocalization, is a concept that covers various structural situations, is a fundamental concept in the definition of aromaticity.[20] Aromaticity is a quantity which cannot be directly measured. Therefore, its magnitude is evaluated in terms of a few criteria, such as structural, energetic and magnetic ones. However, magnetic properties have the closest relationship to aromaticity, since they are directly dependent on the induced ring currents associated with cyclic electron delocalization. There are several methods for evaluating the magnetic aromaticity,[25,26] such as NMR,[27–29] exaltation of magnetic susceptibilities,[29–31] nucleus independent chemical shifts (*NICS*),[26,32–34] ring current density plots,[35–37] and aromatic ring current shieldings (ARCS).[38] *NICS* which was proposed by Schleyer *et al.*,[32] was found to be an easy computed and generally applicable criterion and has been widely used to evaluate the aromaticity and anti-aromaticity of rings,[39,40] clusters,[41,42] transition states,[43,44] and transition metal complexes.[45]

Some new theoretical[46,47] and experimental[48,49] studies have been made on juglone. In the present work, a theoretical study of the IPT process of juglone and its derivatives was realized. Several derivatives of juglone were supposed by placing electron-withdrawing (EW) and electron-releasing (ER) substituents at different positions of phenyl and benzoquinone rings and the effect of substituents on the IPT process was investigated. Next, the influence of IPT on the change of the aromaticity of the phenyl and benzoquinone rings was investigated using magnetic aromaticity indices.

COMPUTATIONAL DETAILS

Density functional theory (DFT) calculation of juglone and its derivatives was conducted in which geometries, energies and thermodynamic functions $\Delta G^{\ominus}$, $\Delta H^{\ominus}$ and $S^{\ominus}_{298}$ values for all structures were calculated at the B3LYP/6-31+G (2d,p) level. The intramolecular proton transfer (IPT) process was performed by ADDREDUNDANT keyword by scanning a proton at the B3LYP/6-31+G (2d,p) level to reach a final optimization. QST2 keyword was used to investigate the transition state structures between the primitive (GS_1) and final (GS_2) structures. The magnetic shielding at the center of a ring system was determined by calculating the chemical shift of "ghost" atoms. By convention, the *NICS* value is the negative of computed isotropic shielding value. Large negative values indicate aromaticity while large positive values represent anti-aromaticity, and near-zero values introduce non-aromaticity. To obtain a measure of the aromaticity in juglone rings, *NICS* values were calculated at two points as illustrated in Fig. 1.

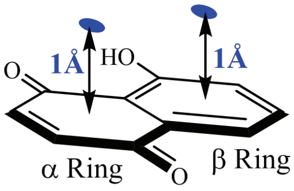


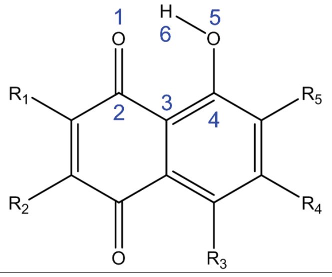
Fig. 1. Definition of the points at which the *NICS* values were calculated.

NICS calculations were performed at 1 Å above the centre of the α- and β-rings for all systems at the B3LYP/6-311+G (2d,p) level and NMR shielding tensors were computed with the continuous set of gauge transformations (CSGT) method. All computations were realized using the Gaussian 98W program package.[50] Data in this article extracted among more than 300 Gaussian program output files.

RESULTS AND DISCUSSION

Geometries and barrier energies

All structures (**MM** and **JG1**–**JG20**) included in this study are shown in Fig. 2. Taking juglone **MM** as the mother molecule, the other structures (**JG1**–**JG20**) can be obtained by placing –OMe, –Br, –Cl and $–NO_2$ substituents at different ring positions of **MM**. The geometry calculations showed all frameworks are almost planar structures. The average bond lengths and bond angles of **MM** and its analogues related to the six-membered ring which formed *via* IPT are given in Table I. The length of the H-bond in the ground state (GS_1) is up to 2 Å; therefore, strong hydrogen bonds exist in all **MM** derivatives. During the IPT process, the average interatomic distance between the donor oxygen (O5) and H6 increased while the distance between the acceptor oxygen (O1) and H6 decreased. In addition, the O1–C2 and C3–C4 bonds lengthened, whereas the C2–C3 and C4–O5 bonds shortened (Table I).



Substituents			Species
R$_2$=R$_3$=R$_4$=R$_5$= H,	R$_1$=	H	**MM**
		NO$_2$	**JG1**
		Cl	**JG6**
		Br	**JG11**
		OMe	**JG16**
R$_1$=R$_3$=R$_4$=R$_5$= H,	R$_2$=	H	**MM**
		NO$_2$	**JG2**
		Cl	**JG7**
		Br	**JG12**
		OMe	**JG17**
R$_1$=R$_2$=R$_4$=R$_5$= H,	R$_3$=	H	**MM**
		NO$_2$	**JG3**
		Cl	**JG8**
		Br	**JG13**
		OMe	**JG18**
R$_1$=R$_2$=R$_3$=R$_5$= H,	R$_4$=	H	**MM**
		NO$_2$	**JG4**
		Cl	**JG9**
		Br	**JG14**
		OMe	**JG19**
R$_1$=R$_2$=R$_3$=R$_4$= H,	R$_5$=	H	**MM**
		NO$_2$	**JG5**
		Cl	**JG10**
		Br	**JG15**
		OMe	**JG20**

Fig. 2. Juglone and its derivatives studied in this work, together with the atom numbering.

In continuation, the IPT of juglone and its derivatives was studied to understand the effect of the location of ER and EW substituents on the IPT process. Since juglone and its derivatives are analogous, their reaction paths are similar. The values of the energy and some thermodynamic functions related to the GS$_1$, TS and GS$_2$ structures are filed in Table II. The barrier energies (E_{rel}, kcal mol^{-1})*

---

* kJ = 4.1868 kcal

of the IPT of the phenolic hydrogen to the carbonyl group for all structures (**MM** and **JG1**–**JG20**) are depicted in Fig. 3. Some substituents at particular positions facilitate the IPT process (when the $E_{\rm rel}$ value is less than that of mother molecule **MM**); however, some others make the progress of the process more arduous (having an $E_{\rm rel}$ value greater than that of **MM**). Two ways are suggested to interpret the effect of substituents on the IPT:

i) locating a particular substituent in different positions (R_1 to R_5) and its effect on the barrier energy; as an example, on placing $-NO_2$ at R_1 to R_5, the activation barriers ($E_{\rm rel}$) of the IPT increase in the order of R_3 (17.69 kcal mol^{-1}) < < R_4 (19.08 kcal mol^{-1}) < R_2 (19.33 kcal mol^{-1}) < R_5 (20.75 kcal mol^{-1}) < R_1 (22.63 kcal mol^{-1}). According to the $E_{\rm rel}$ of **MM** (18.28 kcal mol^{-1}), it can be concluded that substituting a nitro group at the R_3 position facilitates the IPT, while placing it at the other positions, especially at R_1, impedes the reaction. The large effects of substituents at R_1 and R_5 on proton transfer could be related to these substituents neighboring the IPT center, which increases the sensitivity of the IPT to substituents at R_1 and R_5. The influence of substituents located at the other positions can be easily understood according to Fig. 3.

TABLE I. Average bond lengths (Å) and bond angles (degree) in juglone and its derivatives, shown in Fig. 2

Bond	State		
	GS_1	TS	GS_2
	Bond length, r / Å		
O1–C2	1.117	1.259	1.285
C2–C3	1.476	1.230	1.370
C3–C4	1.395	1.421	1.457
C4–O5	1.322	1.258	1.222
O5–H6	0.956	1.290	1.490
H6–O1	1.421	1.175	1.406
	Bond angle, θ / °		
O1–C2–C3	102.2	104.6	122.9
C2–C3–C4	122.9	120.3	120.5
C3–C4–C5	120.0	116.5	123.2
C4–O5–H6	123.7	120.1	104.7
O5–H6–O1	140.7	155.3	156.9

TABLE II. Total energies (Hartree), activation barrier energies ($E_{\rm rel}$ / kcal mol^{-1}), zero-point vibrational energies ($ZPVE$ / kcal mol^{-1}), $\Delta G^{\ominus}$, $\Delta H^{\ominus}$ and $S^{\ominus}_{298}$ calculated at the B3LYP/6--31+G(2d,p) level for all structures shown in Fig. 2

Species	State	B3LYP/6-31+G(2d,p)	$E_{\rm rel}$	$ZPVE$	$G^{\ominus}_{298} - G^{\ominus}_{0}$	$H^{\ominus}_{298} - H^{\ominus}_{0}$	$S^{\ominus}_{298}$
MM	GS_1	–606.8297	(0.00)	93.384	–0.0345	0.0098	93.347
	TS	–606.8006	(18.28)	90.326	–0.0340	0.0093	91.200
	GS_2	–606.8049	(15.55)	88.072	–0.0332	0.0089	88.575
	GS_1	–810.3016	(0.00)	95.525	–0.0385	0.0114	106.873

TABLE II. Continued

Species	State	B3LYP/6-31+G(2d,p)	$E_{\rm rel}$	*ZPVE*	$G^{\ominus}_{298} - G^{\ominus}_{0}$	$H^{\ominus}_{298} - H^{\ominus}_{0}$	$S^{\ominus}_{298}$
JG1	TS	–810.2655	(22.63)	92.442	–0.0380	0.0109	104.989
	GS_2	–810.2703	(19.66)	95.360	–0.0385	0.0114	106.929
	GS_1	–810.2975	(0.00)	95.504	–0.0386	0.0114	107.313
JG2	TS	–810.2667	(19.33)	92.442	–0.0381	0.0111	105.133
	GS_2	–810.2728	(15.50)	95.360	–0.0384	0.0114	106.998
	GS_1	–810.2967	(0.00)	95.468	–0.0383	0.0114	106.487
JG3	TS	–810.2685	(17.69)	92.454	–0.0378	0.0108	104.469
	GS_2	–810.2724	(15.25)	95.289	–0.0385	0.0114	107.021
	GS_1	–810.3101	(0.00)	95.481	–0.0388	0.0114	107.684
JG4	TS	–810.2797	(19.08)	92.463	–0.0385	0.0016	106.107
	GS_2	–810.2842	(16.25)	95.289	–0.0128	0.0375	108.042
	GS_1	–810.3016	(0.00)	95.525	–0.0385	0.0630	106.874
JG5	TS	–810.2685	(20.75)	92.457	–0.0380	0.0118	104.948
	GS_2	–810.2784	(14.54)	95.447	–0.0384	0.0123	106.742
	GS_1	–1065.7223	(0.00)	87.038	–0.0365	0.0110	100.155
JG6	TS	–1065.6919	(19.07)	83.975	–0.0360	0.0105	97.950
	GS_2	–1065.6959	(16.57)	82.616	–0.0351	0.0100	95.138
	GS_1	–1065.7229	(0.00)	87.048	–0.0386	0.0110	100.147
JG7	TS	–1065.6934	(18.48)	83.968	–0.0381	0.0105	97.950
	GS_2	–1065.6982	(15.49)	82.561	–0.0384	0.0100	95.138
	GS_1	–1065.7134	(0.00)	86.806	–0.0371	0.0111	101.594
JG8	TS	–1065.6875	(16.25)	83.819	–0.0362	0.0106	98.512
	GS_2	–1065.6917	(13.64)	83.448	–0.0350	0.0996	94.832
	GS_1	–1065.7266	(0.00)	86.896	–0.0365	0.0110	100.130
JG9	TS	–1065.6979	(18.00)	83.847	–0.0392	0.0105	98.018
	GS_2	–1065.7026	(15.06)	82.549	–0.0362	0.0100	95.293
	GS_1	–1065.7226	(0.00)	86.988	–0.0364	0.0110	99.969
JG10	TS	–1065.6946	(17.57)	83.954	–0.0360	0.0037	97.936
	GS_2	–1065.6993	(14.62)	82.952	–0.0416	0.0105	95.398
	GS_1	–3176.3125	(0.00)	86.710	–0.0376	0.0112	102.679
JG11	TS	–3176.2823	(18.96)	83.662	–0.0370	0.0107	100.468
	GS_2	–3176.2861	(16.55)	86.577	–0.0374	0.0112	102.264
	GS_1	–3176.3127	(0.00)	86.713	–0.0376	0.0112	102.679
JG12	TS	–3176.2834	(18.41)	83.631	–0.0370	0.0104	100.482
	GS_2	–3176.2881	(15.44)	86.633	–0.0375	0.0112	102.396
	GS_1	–3176.3033	(0.00)	86.556	0.0382	0.0113	104.282
JG13	TS	–3176.2774	(16.26)	83.566	–0.0372	0.0108	101.041
	GS_2	–3176.2814	(13.73)	86.482	–0.0377	0.0112	102.977
	GS_1	–3176.3160	(0.00)	86.546	–0.0376	0.0113	102.822
JG14	TS	–3176.2871	(18.14)	83.484	–0.0371	0.0108	100.691
	GS_2	–3176.2918	(15.21)	86.498	–0.0375	0.0112	102.621
	GS_1	–3176.3131	(0.00)	86.699	–0.0375	0.0112	102.544
JG15	TS	–3176.2852	(17.49)	83.654	–0.0370	0.0108	100.527
	GS_2	–3176.2898	(14.62)	86.659	–0.0375	0.0112	102.404
	GS_1	–720.7170	(0.00)	115.329	–0.0382	0.0125	106.998
JG16	TS	–720.6871	(18.73)	112.257	–0.0376	0.0120	104.675

TABLE II. Continued

Species	State	B3LYP/6-31+G(2d,p)	E_{rel}	$ZPVE$	$G^{\ominus}_{298}-G^{\ominus}_{0}$	$H^{\ominus}_{298}-H^{\ominus}_{0}$	$S^{\ominus}_{298}$
JG16	GS_2	–720.6911	(16.23)	110.680	–0.0354	0.0107	97.187
	GS_1	–720.7225	(0.00)	115.700	–0.0377	0.0113	105.259
JG17	TS	–720.6949	(17.31)	112.601	–0.0370	0.0108	103.064
	GS_2	–720.6980	(15.34)	110.945	–0.0353	0.0096	96.767
	GS_1	–720.7076	(0.00)	115.163	–0.0380	0.0125	106.399
JG18	TS	–720.6809	(16.78)	112.129	–0.0375	0.0120	104.319
	GS_2	–720.6861	(13.47)	110.968	–0.0350	0.0107	96.803
	GS_1	–720.7230	(0.00)	115.483	–0.0378	0.0124	105.630
JG19	TS	–720.6937	(18.43)	112.359	–0.0374	0.0119	103.956
	GS_2	–720.6972	(16.21)	110.554	–0.0354	0.0107	97.141
	GS_1	–720.7142	(0.00)	115.567	–0.0377	0.0123	105.530
JG20	TS	–720.6862	(17.53)	112.530	–0.0372	0.0118	103.237
	GS_2	–720.6924	(13.68)	115.615	–0.0160	0.0122	105.064

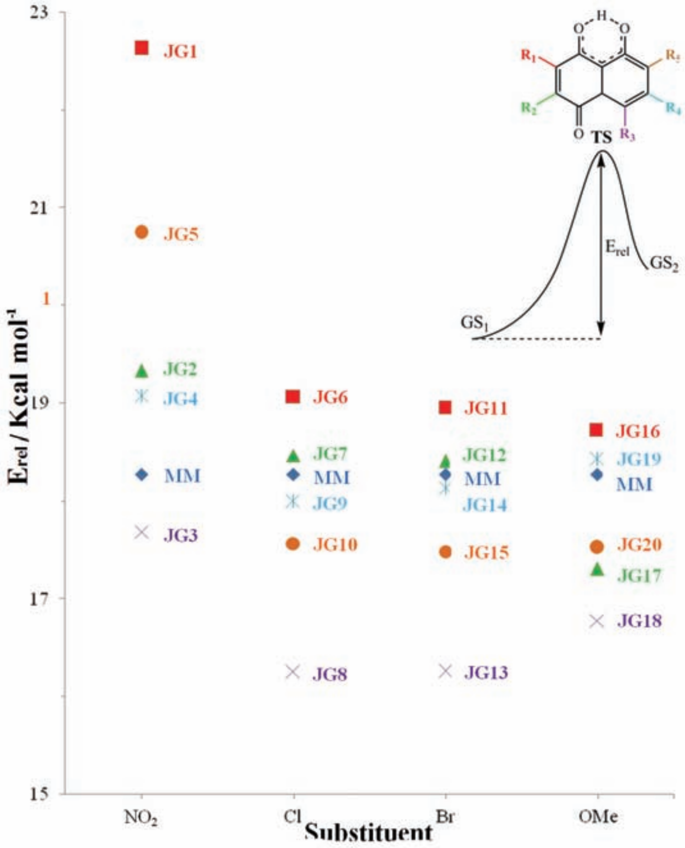


Fig. 3. The barrier energies (E_{rel} / kcal mol^{-1}) for the IPT of **MM** and the **JG1–JG20** analogues included in this study. (R_1 = square sign, R_2 = triangle sign, R_3 = multiplication sign, R_4 = star sign, R_5 = circle sign. **MM** showed by rhombic sign).

ii) Placing different substituents at a particular position and their influence on the barrier energy; For instance, locating the above-mentioned groups at the R_5 position indicated that –OMe, –Br and –Cl groups have promoting effects on the IPT whereas $–NO_2$ has retarding effects on the reaction. The strong conjugation of the $–NO_2$ group with the aromatic ring with respect to other substituents leads the IPT reaction being hindered. In addition, substituting R_1 with any group encumbers the IPT since **MM** has a lower E_{rel} value than all the R_1-substituted compounds (E_{rel}: **MM** < **JG16** < **JG11** < **JG6** < **JG1**). The highest relative barrier energy for the $–NO_2$ group at **JG1** may be attributed to the repulsion energy between the non-bonding electrons on the oxygen atoms of the $–NO_2$ substituent and the –OH group, which is greater than the repulsion energy between the $–NO_2$ substituent and the –CO group. By the same interpretation, substituting R_3 with any group facilitates the IPT.

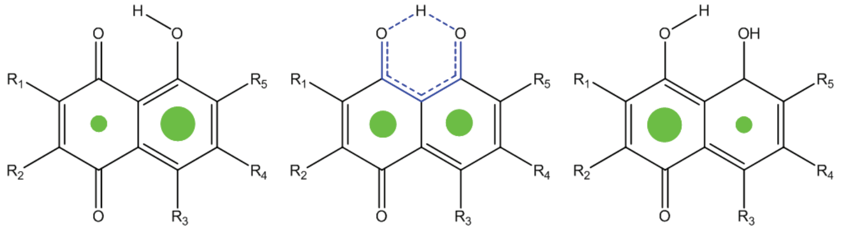
Effect of the IPT on the NICS value of the rings

Perturbation of the π-electron density distribution depends on the electronic properties of the substituents and can be studied using *NICS* values. Hence, *NICS* values for the GS_1, TS and GS_2 structures of all **MM** derivatives were calculated and are given in Table III, from which, it can be clearly seen that all structures in GS_1 have negative *NICS* values in the *β*-ring due to the aromaticity of this ring and have positive ones in the *α*-ring because of the localized quinone ring. Furthermore, by comparing the *NICS* values of the GS_1 and GS_2 structures, it was

TABLE III. *NICS*(1) values (ppm) obtained using the CSGT procedure at the B3LYP/6-311+G(2d,p) level for the ground states and transition state structures of each species

Substituent	State	Position									
		R_1		R_2		R_3		R_4		R_5	
		Ring									
		α	*β*	*α*	*β*	*α*	*β*	*α*	*β*	*α*	*β*
–H	GS_1	2.0	–8.0	2.0	–8.0	2.0	–8.0	2.0	–8.0	2.0	–8.0
	TS	1.5	–5.1	1.5	–5.1	1.5	–5.1	1.5	–5.1	1.5	–5.1
	GS_2	1.1	–2.3	1.1	–2.3	1.1	–2.3	1.1	–2.3	1.1	–2.3
$–NO_2$	GS_1	1.6	–8.0	1.7	–7.9	0.7	–8.0	1.7	–8.5	1.8	–8.1
	TS	0.6	–4.7	1.6	–5.2	0.5	–5.9	1.5	–5.9	1.5	–5.5
	GS_2	0.3	–2.3	0.5	–2.2	0.4	–3.1	1.0	–3.3	0.8	–3.0
–Cl	GS_1	2.0	–8.2	1.9	–7.9	1.5	–7.8	2.0	–7.7	1.9	–8.1
	TS	1.4	–5.2	1.7	–5.2	0.8	–5.1	1.6	–5.1	1.6	–5.2
	GS_2	0.8	–2.3	0.9	–2.3	0.6	–2.9	1.2	–2.7	1.0	–2.5
–Br	GS_1	1.7	–8.2	1.8	–7.9	1.8	–7.9	1.6	–7.8	1.3	–8.1
	TS	1.4	–5.2	1.7	–5.0	1.5	–5.1	1.7	–5.0	1.6	–5.2
	GS_2	0.4	–2.5	1.0	–2.3	0.8	–2.5	0.5	–3.4	0.0	–2.8
–OMe	GS_1	1.7	–8.0	2.0	–7.9	3.0	–8.1	1.7	–7.4	2.0	–7.7
	TS	1.6	–5.2	1.9	–5.5	1.1	–5.3	0.9	–4.8	1.3	–5.0
	GS_2	0.9	–2.3	1.4	–2.9	0.1	–1.9	1.9	–4.8	0.6	–2.0

found that during IPT from the β- to the α-ring, the aromatic properties and the π-electron delocalization in β-ring decreased, whereas the π-electron delocalization in the α-ring increased for all **MM** analogues (Table III and Fig. 4). In continuation, the changing rate of the aromatic properties and the π-electron delocalization due to placing substituents at different positions on the rings were studied. Thus the, *NICS* value of the initial state (GS$_1$) was subtracted from that of the final state (GS$_2$), *i.e.*, $\Delta(NICS) = NICS_{(GS2)} - NICS_{(GS1)}$. Analysis of the $\Delta(NICS)$ values for the α-ring showed that highest and lowest rates of increase in π-electron delocalization in this ring were with –OMe at the R$_3$ (2.9 ppm) and R$_4$ (0.2 ppm) positions, respectively. The same analysis for the β-ring indicated that maximum and minimum rates of decrease in π-electron delocalization were with –OMe at the R$_3$ (6.2 ppm) and –Br at the R$_4$ (4.4 ppm) positions, respectively.



State	GS$_1$		TS		GS$_2$	
Ring	α	β	α	β	α	β
NICS (1)	1.85 ±1.15	-7.95 ±0.55	1.20 ±0.70	-5.30±0.60	0.95 ±0.95	-3.35 ±1.45

Fig. 4. Distribution of the hanging π-electron density during IPT (shown by green circles) and range of *NICS* (1) values (ppm) in the α- and β-rings for the GS$_1$, TS and GS$_2$ structures (shown under the figure).

CONCLUSIONS

In the present study, intramolecular proton transfer of juglone and 20 of its derivatives were studied. Placing a number of groups at certain ring positions facilitated the IPT, whereas placing some others at specific positions impeded the reaction. As noticeable examples, locating –Cl and –Br groups in the R$_3$ position (**JG8** and **JG13** analogues, respectively) resulted in a significant decrease in the activation barrier which effectively increased the realization of the IPT more than other analogues, whereas placing an –NO$_2$ group at the R$_1$ position (**JG1** analogue) remarkably increased the activation barrier, which hindered the progress of the reaction compared to the other derivatives.

Analysis of the *NICS* values showed that all GS$_1$ structures had negative *NICS* values in the β-ring (due to the aromaticity of the β-ring) and positive ones in the α-ring (because of the localized quinone ring). Furthermore, during IPT from the β- to the α-ring, the aromatic properties in the β-ring downgraded (due to destruction of the aromatic cycle), whereas the π-electron delocalization in the α-ring were upgraded (because of the newly formed double bond) for all **MM** analogues. It should be noted that all derivatives showed different rates of change of the aromatic properties of the α- and β-rings.

Since Juglone is a natural ligand and IPT can be a basis for formation of complexes, juglone and its analogues can be utilized as absorbents or carriers of metal ions and amino acids in biologic systems. According to the calculation results, it can be rationalized which derivates of juglone can be utilized as an absorbent (derivatives which facilitate the IPT) and which ones as a carrier (derivatives which hinder the progress of the IPT) of metal ions and amino acids.

ИЗВОД

ТЕОРИЈСКО ИСТРАЖИВАЊЕ ИНТРАМОЛЕКУЛСКОГ ТРАНСФЕРА ПРОТОНА И ОД ЈЕЗГРА НЕЗАВИСНОГ ХЕМИЈСКОГ ПОМАКА У ЈУГЛОНУ И ЊЕГОВИМ ДЕРИВАТИМА

E. VESSALLY[1], E. FEREYDUNI[2], M. KAMAEE[3] и S. MORADI[4]

[1]*Payame Noor University (PNU), Zanjan,* [2] *Department of Chemistry, Tabriz Branch, Islamic Azad University, Tabriz,* [3]*Department of Chemistry, Shahid Chamran University, Ahvaz и* [4]*Faculty of Chemistry, Islamic Azad University, North Tehran Branch, Tehran, Iran*

У раду се прво истражује интрамолекулски трансфер протона (IPT) у југлону и његовим дериватима. Ова истраживања односе се на утицај електрон-привлачних и електрон-одбојних супституената у различитим положајима у југлону. Проучавани су IPT процеси у којима су геометрије, енергије и термодинамичке функције једињења одређене методом функционалне теорије густине (DFT), на нивоу B3LYP/6-31+G(2d,p). Затим је проучаван утицај IPT на промену ароматичности фенил и бензохинонског прстена. За то су израчунате *NICS*-вредности прстенова, за основна и прелазна стања (GS_1, TS и GS_2) примењујући CSGT процедуру на нивоу B3LYP/6-31+G(2d,p).

(Примљено 30. септембра 2010)

REFERENCES

1. R. H. Thomson, *Naturally Occurring Quinones*, Academic Press, London, 1971
2. S. A. A. Osman, A. A. Abdalla, M. O. Alaib, *J. Pharm. Sci.* **72** (1983) 68
3. I. M. Roushdi, E. S. A. Ibrahim, N. S. Habib, *Pharmazie* **31** (1976) 856
4. B. A. Kulkari, V. D. Kelker, P. L. Kukarni, *Indian J. Pharm. Sci.* **45** (1983) 21
5. R. I. Brinkworth, D. P. Fairlie, *Biochim. Biophys. Acta* **1253** (1995) 5
6. L. Salmon-Chemin, E. Buisine, V. Yardley, S. Kohler, M. A. Debreu, V. Landry, C. Sergheraert, S. L. Croft, L. R. Krauth-Siegel, E. Davioud-Charvet, *J. Med. Chem.* **44** (2001) 548
7. B. Hazra, P. Sur, D. K. Roy, B. Sur, A. Banerjee, *Planta. Med.* **51** (1984) 295
8. V. Yardley, D. Snowdon, S. Croft, B. Hazra, *Phytother. Res.* **10** (1996) 559
9. F. J. Bullock, J. F. Tweedie, D. D. McRitchie, M. A. Tucker, *J. Med. Chem.* **13** (1970) 550
10. N. B. Perry, J. W. Blunt, *Nat. Prod.* **54** (1991) 978
11. H. Bobich, A. Stern, *J. Appl. Toxicol.* **13** (1993) 353
12. J. J. Inbaraj, C. F. Chignell, *Chem. Res. Toxicol.* **17** (2004) 55

13. Z. Varga, L. Bene, C. Pieri, S. Damjanovich, R. Gaspar, *Biochem. Biophys. Res. Commun.* **218** (1996) 828
14. A. Kovacs, I. Mascari, I. Hargittai, *J. Phys. Chem. A* **103** (1999) 3110
15. M. Cuma, S. Scheiner, T. Kar, *J. Mol. Struct. THEOCHEM* **467** (1999) 37
16. S. F. Tayyari, H. Raissi, F. Milani-Nejad, I. S. Butler, *Vib. Spectrosc.* **26** (2001) 187
17. R. Kakkar, V. Katoch, *J. Mol. Struct. THEOCHEM* **578** (2002) 169
18. D. Devault, *Quantum Mechanical Tunnelling in Biological Systems*, Cambridge Univ. Press, London, 1984
19. L. I. Krishtalik, *Biochim. Biophys. Acta* **1458** (2000) 6
20. T. M. Krygowski, B. T. Stepien, *Chem. Rev.* **105** (2005) 3482
21. T. M. Krygowski, M. K. Cyranski, Z. Czarnocki, G. Haefelinger, A. R. Katritzky, *Tetrahedron* **56** (2000) 1783
22. F. D. Proft, P. Geerlings, *Chem. Rev.* **101** (2001) 1451
23. X. Li, A. E. Kuznetsov, H. F. Zhang, A. I. Boldyrev, L. S. Wang, *Science* **291** (2001) 859
24. E. D. Jemmis, B. Kiran, *Inorg. Chem.* **37** (1998) 2110
25. J. A. N. F. Gomes, R. B. Mallion, *Chem. Rev.* **101** (2001) 1349
26. Z. Chen, C. S. Wannere, C. Corminboeuf, R. Puchta, P. v. R. Schleyer, *Chem. Rev.* **105** (2005) 3842
27. R. H. Mitchell, *Chem. Rev.* **101** (2001) 1301
28. F. Faglioni, A. Ligabue, S. Pelloni, A. Soncini, R. G. Viglione, M. B. Ferraro, R. Zanasi, P. Lazzeretti, *Org. Lett.* **7** (2005) 3457
29. J. A. Pople, *J. Chem. Phys.* **24** (1956) 1111
30. D. W. Davies, *The theory of the electric and magnetic properties of molecules*, Wiley, London, 1967
31. R. C. Benson, W. H. Flygare, *J. Am. Chem. Soc.* **92** (1970) 7523
32. P. v. R. Schleyer, C. Maerker, A. Dransfeld, H. Jiao, N. J. R. v. E. Hommes, *J. Am. Chem. Soc.* **118** (1996) 6317
33. M. K. Cyranski, T. M. Krygowski, A. L. Katritzky, P. v. R. Schleyer, *J. Org. Chem.* **67** (2002) 1333
34. C. Corminboeuf, T. Heine, G. Seifert, P. v. R. Schleyer, J. Weber, *Phys. Chem. Chem. Phys.* **6** (2004) 273
35. E. Steiner, P. W. Fowler, *Chem. Commun.* (2001) 2220
36. T. M. Krygowski, K. Ejsmont, B. T. Stepien, M. K. Cryanski, J. Poater, M. J. Sola, *Org. Chem.* **69** (2004) 6634
37. T. M. Krygowski, B. T. Stepien, M. K. Cryanski, K. J. Ejsmont, *Org. Chem.* **18** (2005) 886
38. J. Juselius, D. Sundholm, *Phys. Chem. Chem. Phys.* **1** (1999) 3429
39. G. Subramanian, P. v. R. Schleyer, H. Jiao, *Angew. Chem. Int. Ed. Engl.* **35** (1996) 2638
40. T. Zywietz, H. Jiao, P. v. R. Schleyer, A. de Meijere, *J. Org. Chem.* **63** (1998) 3417
41. A. Hirsch, Z. Chen, H. Jiao, *Angew. Chem. Int. Ed.* **39** (2000) 3915
42. M. Bühl, A. Hirsch, *Chem. Rev.* **101** (2001) 1153
43. F. P. Cossio, I. Marao, H. Jiao, P. v. R. Schleyer, *J. Am. Chem. Soc.* **121** (1999) 6737
44. S. P. Verevkin, H. D. Beckhaus, C. Rückhardt, R. Haag, S. I. Kozhushkov, T. Zywietz, A. de Meijere, H. Jiao, P. v. R. Schleyer, *J. Am. Chem. Soc.* **120** (1998) 11130
45. P. v. R. Schleyer, B. Kiran, D. V. Simon, T. S. Sorensen, *J. Am. Chem. Soc.* **122** (2000) 510

46. R. Jin, *J. Mol. Struct. THEOCHEM* **939** (2010) 9
47. S. Sharma, B. K. Sharma, Y. S. Prabhakar, *Eur. J. Med. Chem.* **44** (2009) 2847
48. Y.-B. Ji, Z.-Y. Qu, X. Zou, *Exp. Toxicol. Pathol.* **63** (2011) 69
49. B. K. Aithal, M. R. S. Kumar, B. N. Rao, N. Udupa, B. S. S. Rao, *Cell. Biol. Int.* **33** (2009) 1039
50. *Gaussian 98 software package*, Gaussian Inc., Wallingford, CT, 1998.