ISSN 1070-4280, Russian Journal of Organic Chemistry, 2006, Vol. 42, No. 10, pp. 1464–1468. © Pleiades Publishing, Inc., 2006.
Original Russian Text © V.Ya. Fain, B.E. Zaitsev, M.A. Ryabov, 2006, published in Zhurnal Organicheskoi Khimii, 2006, Vol. 42, No. 10, pp. 1479–1483.

Tautomerism of Anthraquinones: III.* Tautomerization and Rotational Isomerization as Processes Responsible for the Appearance of Several π_l,π^*-Bands in the Absorption Spectra of Hydroxy-Substituted Quinones

V. Ya. Fain, B. E. Zaitsev, and M. A. Ryabov

Russian University of Peoples' Friendship, P.O. Box 453, Moscow, 127349 Russia
e-mail: vfain@mail.ru

Received June 30, 2005

Abstract—Hydroxy-substituted anthraquinones, naphthoquinones, and naphthacenequinones exist as equilibrium mixtures of different tautomers and rotational isomers which give rise to several π_l,π^* bands in their electronic absorption spectra. Each π_l,π^* band can be assigned to a particular tautomer and conformer on the basis of the substituent constants σ^A.

DOI: 10.1134/S1070428006100101

Persistent interest in anthraquinone derivatives originates from their wide application as dyes (both natural and synthetic), biologically active substances, medical agents, analytical reagents, indicators, catalysts for industrially important processes, materials for data storage and processing devices, etc. [2]. Numerous natural compounds have hydroxyanthraquinone structures, and their color and biological activity depends on the number and mutual arrangement of the hydroxy groups. The presence of several π_l,π^* bands in a single electronic absorption spectrum of hydroxyanthraquinones contradict the results of quantum-chemical calculations which predict only one π_l–π^* transition for each particular α-hydroxyanthraquinone [3]. We previously showed that such spectral pattern results from prototropic tautomerism of these compounds. However, the number of experimental π_l,π^* bands often exceeds the number of possible tautomers [1, 4], and no rationalization has been proposed so far for this fact.

In the present study we showed that, depending on the conditions, hydroxyanthraquinones may exist as equilibrium mixtures of both different tautomers and different rotational isomers. Each structure is characterized by its own single π_l,π^*-absorption band, and the appearance of several π_l,π^* bands in an experimental spectrum indicates the existence of tautomeric and conformational equilibria. Each hydroxy group in a particular structure may be free (OH) (i.e., not involved in intramolecular hydrogen bonding with the carbonyl oxygen atom), H-bonded (OH*), or ionized (O^-; in alkaline medium).

The experimental π_l,π^* bands may be assigned to different tautomers and conformers on the basis of correlations with the sums of the constants σ^A of OH, OH*, and O^- substituents. The constants σ^A_α and σ^A_β proposed for α- and β-substituted 9,10-anthraquinones [5] characterize the donor–acceptor power of a substituent X in intramolecular charge transfer along the X–(CH=CH)$_n$–C=O fragment, which is responsible for the position of the π_l,π^* band in the electronic absorption spectrum. Aprotic substituents, i.e., those incapable of forming intramolecular hydrogen bond with the neighboring carbonyl group give rise to the following linear correlation between σ^A_α and σ^A_β:

$$\sigma^A_\beta = (0.935 \pm 0.012)\sigma^A_\alpha + (0.07 \pm 0.01);\ r = 0.9990. \quad (1)$$

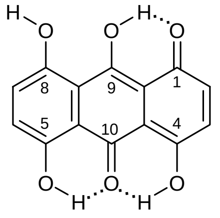
The point for the hydroxy group deviates from this straight line, but it fits another analogous dependence found for substituents capable of forming intramolecular hydrogen bond with the neighboring carbonyl group [5]. From Eq. (1), we can calculate the value σ^A_α(OH) for free hydroxy group in 9,10-anthraquinone; it is equal to –0.49.

The hydroxy groups in potentially tautomeric anthraquinones, e.g., in 4,5,8,9-tetrahydroxy-1,10-anthra-

---

* For communication II, see [1].

quinone (**I**), may occupy different α- and *meso*-positions and may be both free and H-bonded.



I

A correlation between the position of π_l,π^* band and constants σ^A would conform to a single isostructural series if separate scales of σ^A for substituents in the α- and *meso*-positions are used. The application of constants σ^A is based on the proportional response principle [5], according to which analogous changes in the structure of compounds lead to proportional shifts of their absorption maxima. The values of λ_{max} of tautomeric α-hydroxyanthraquinones are linearly related to the number of hydroxy groups [1]. These relations allow determination of constants σ^A to be performed in different ways, from both experimental values of λ_{max} in various solvents and those calculated by quantum-chemical methods. In addition, constants σ^A can be determined from linear relations between these parameters for isomeric anthraquinones, e.g., by Eq. (2) for 1,10- and 1,5-anthraquinones. The σ^A values (Table 1) do not depend on the calculation method.

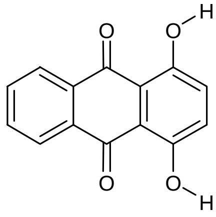
Table 1. Constants σ^A of the hydroxy and oxido groups for tautomeric anthraquinones

Constant	Tautomer			
	9,10	1,4	1,10	1,5
σ_{α}^{A}(OH)	–0.49	–0.66	–0.67	–0.85
σ_{α}^{A}(OH*)	–0.62	–0.81	–0.81	–1.00
σ_{α}^{A}(O^-)	–1.01	–1.25	–1.23	–1.45
σ_{meso}^{A}(OH)	–	–0.58	–0.60	–0.77
σ_{meso}^{A}(OH*)	–	–0.71	–0.72	–0.90
σ_{meso}^{A}(O^-)	–	–1.10	–1.09	–1.30

$$\sigma^A(1,5) = (1.0770\pm0.0035)\sigma^A(1,10) - (0.126\pm0.003); \quad (2)$$

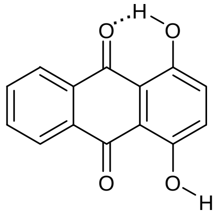
$$N = 6,\ r = 0.99998,\ s = 0.002.$$

The existence of numerous linear relations between the experimental values of ν_{max} for different α-hy-



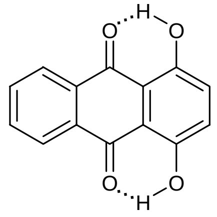
1,4-(OH)$_2$-9,10

II



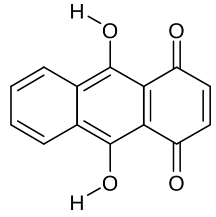
1-OH*-4-OH-9,10

III



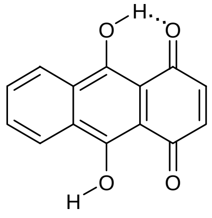
1,4-(OH*)$_2$-9,10

IV



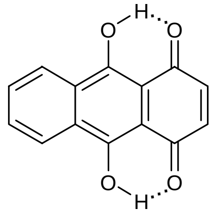
9,10-(OH)$_2$-1,4

V



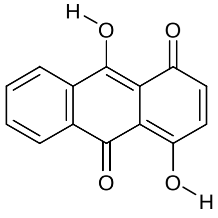
9-OH*-10-OH-1,4

VI



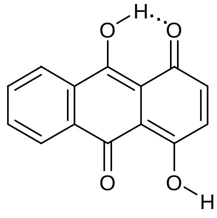
9,10-(OH*)$_2$-1,4

VII



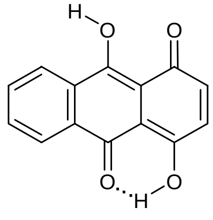
4,9-(OH)$_2$-1,10

VIII



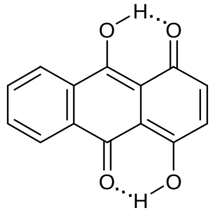
4-OH-9-OH*-1,10

IX



4-OH*-9-OH-1,10

X



4,9-(OH*)$_2$-1,10

XI

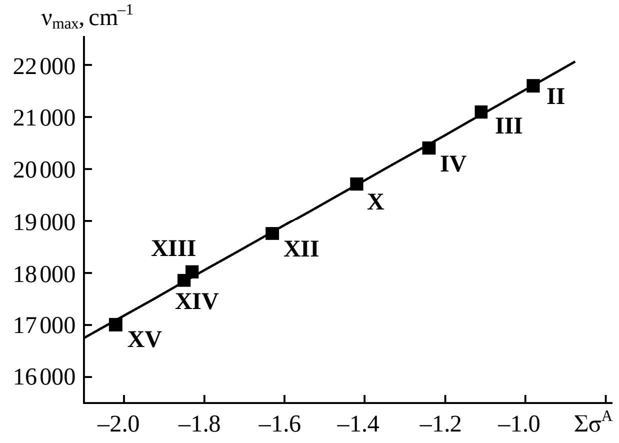
Table 2. π_l,π^*-Absorption maxima in the electronic spectra of α-hydroxyanthraquinones

Position of OH groups	Solvent	λ_{max}, nm													Reference
		9,10					1,4			1,10			1,5		
		4^a	3^a	2^a	1^a	0^a	2^a	1^a	0^a	2^a	1^a	0^a	2^a	0^a	
1	Hexane				386^b	406						423			[7]
1,5	Ethanol				397^b	418						437			[7]
1,8	Hexane			411	421	431.5					445.5	458.5			[7]
1,4	Gas phase			463.5^b	473.6^b		481.5	492.6	504			513.7			[8]
1,4	Hexane			459	476	486				498	507.5	520			[6]
1,4	Methanol			463^b	474	490^b					507^b				[6]
1,4,5	Cyclo-hexane		462^b	472	483	495				505^b	517	530	562		[7, 9]
1,4,5	Methanol		457^b			490					510^b	525^b			[7]
1,4,5,8	Heptane	477.5	487.5		509.5	521		535^b	546	533		559.5	592.5		[10]
1,4,5,8	Ethanol		486.5		508	519			544			558		604	[7]

[a] Number of broken intramolecular hydrogen bonds.
[b] Shoulder.

droxyanthraquinones and the sum of the substituent constants σ^A indicates that each π_l,π^* band belongs to a particular structure and makes it possible to determine mutual arrangement of free and H-bonded hydroxy groups.

Let us consider the procedure for correlation analysis of π_l,π^*-absorption bands using quinizarin as an example. This compound exists as three tautomers having 9,10-, 1,4-, and 1,10-anthraquinoid structures, and each tautomer could give rise to rotational isomers, **II**–**IV**, **V**–**VII**, and **VIII**–**XI**, respectively. Each conformer is characterized by the sum of constants σ^A for free and H-bonded hydroxy groups. Likewise, each tautomeric quinizarin monoanion can exist as two conformers in which the non-ionized hydroxy group may be involved in intramolecular hydrogen bond or not. Quinizarin dianions can exist as three tautomers.



Correlation between ν_{max} of π_l,π^* bands in the electronic absorption spectra of quinizarin and its anions in methanol and the sum of substituent constants σ^A: **XII**, 4-OH-1-O$^-$-9,10; **XIII**, 9-OH-4-O$^-$-1,10; **XIV**, 4-OH-9-O$^-$-1,10; **XV**, 1,4-(O$^-$)$_2$-9,10. For numbering of the other conformers, see text.

The experimental π_l,π^* bands are assigned on the basis of correlations between ν_{max} with the sums of the corresponding constants σ^A. Figure and Eq. (3) illustrate such a correlation for quinizarin (Table 2) and its anions [6].

$$\nu_{max}\ (\mathrm{cm}^{-1}) = (4342 \pm 67)\Sigma\sigma^A + (25861 \pm 104); \quad (3)$$
$$N = 8,\ r = 0.9993,\ s = 67.$$

Equal $\Sigma\sigma^A$ values for some conformers may be the reason for ambiguous assignment of some π_l,π^* bands on the basis of spectrophotometric data. For example, ν_{max} 19720 cm^{-1} (λ_{max} 507 nm) may be assigned equally to conformers **VII** and **X** ($\Sigma\sigma^A$ = –1.42 and –1.41, respectively). If a dynamic equilibrium exists between two species, the more stable of these is preferred. The stability of a compound in the gas phase is characterized by its energy of atomization ΔH, and in solution, by the solvation coefficient M [6]. The latter are greater for all 1,10-quinoid tautomers compared to 1,4-anthraquinoid structures [6]. Therefore, the π_l,π^* band with λ_{max} 507 nm corresponds to structure **X**.

Tautomeric and conformational equilibria occur both in solution and in the gas phase. This follows, e.g., from the linear correlation between ν_{max} for all six

π_l,π^* bands of quinizarin in the gas phase (Table 2) and the sum of constants σ^A of hydroxy groups ($r = 0.997$, $s = 66$).

The above relations allowed us to refine the tautomeric composition of quinizarin: it exists in solution as 9,10- and 1,10-quinoid structures, while all three possible tautomers occur in the gas phase.

Equation (4) describes the correlation between ν_{max} and $\Sigma\sigma^A$ for 1,4,5-trihydroxyanthraquinone in cyclohexane; the tautomeric and conformational composition of this compound is given in Table 2.

$$\nu_{max}\ (\text{cm}^{-1}) = (3744 \pm 73)\Sigma\sigma^A + (27140 \pm 142); \quad (4)$$
$$N = 8,\ r = 0.9989,\ s = 65.$$

The values of λ_{max} for π_l,π^* bands of conformers are linearly related to the number of intramolecular hydrogen bonds (m). For example, Eq. (5) was deduced for 1,4,5,8-tetrahydroxy-9,10-anthraquinone in heptane:

$$\lambda_{max}\ (\text{nm}) = (10.90 \pm 0.71)m + (477.1 \pm 0.4); \quad (5)$$
$$N = 4,\ r = 0.99975,\ s = 0.5.$$

The above relations made it possible to reveal some unobvious and even unexpected specific structural features of the compounds under study. Conformational equilibria in solution are most typical of 9,10- and 1,10-anthraquinones. Three of the six tautomers and conformers of quinizarin in the gas phase have 1,4-quinoid structure, and four species possess free hydroxy groups; however, no tautomer with the most expected 1,4-$(OH^*)_2$-9,10-anthraquinone structure was found. Among theoretically possible conformers of 1,4,5,8-tetrahydroxy-9,10-anthraquinone, the symmetric one possessing two intramolecular hydrogen bonds does not exist even in neutral hydrocarbons. Tri- and tetrahydroxy-1,5-anthraquinones in solutions in hydrocarbons have no intramolecular hydrogen bonds, which is likely to indicate their nonplanar structure; on the other hand, intramolecular hydrogen bonds are conserved in ethanol.

As $\Sigma\sigma^A$ increases, the ΔH and M values decrease [6]. The constants σ^A for free OH groups are smaller than those for hydroxy groups involved in intramolecular hydrogen bonds (Table 1). It follows that rupture of intramolecular hydrogen bond is accompanied by increase in the stability of conformers, which cannot be attributed solely to enhancement of intermolecular interactions with the solvent. This is one more unexpected consequence, which is inconsistent with the generally accepted views on the role of intramolecular hydrogen bonding.

The regular character of the revealed relations, extremely high values of r, and low values of s make no doubt in their reliability, even if the number of points is minimal. In the preceding communication [1] we noted relatively poor (<0.990) coefficients r for some correlations and presumed that these values suggest a more complex character of the corresponding dependences. Now it has become clear that the reason for the observed deviations is the lack of due account taken of conformational equilibria.

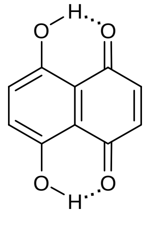
Our results indicate that the conventional views implying exclusively 9,10-quinoid structure of anthraquinones and necessary formation of intramolecular hydrogen bonds between the carbonyl and hydroxy groups in the *peri* position with respect to each other should be revised. Our concepts made it possible to rationalize for the first time the appearance of numerous π_l,π^* bands in the electronic absorption spectra of hydroxyanthraquinones. The procedure based on the use of substituent constants σ^A is an effective tool for prediction of the position of π_l,π^* bands of any α-hydroxyanthraquinone tautomer and conformer.

The proposed approach turned out to be applicable not only to hydroxyanthraquinones but also to other related quinones. For example, the electronic absorption spectrum of 5,8-dihydroxy-1,4-naphthoquinone (**XVI**) in chloroform [11] contains four π_l,π^* bands. Correlation analysis by Eq. (6) showed that these bands should be assigned as follows: λ_{max} 490 nm, 5,8-$(OH)_2$-1,4; 524 nm, 5,8-$(OH^*)_2$-1,4; 547 nm, 4-OH*-8-OH-1,5; and 564 nm, 4,8-$(OH^*)_2$-1,5. Here, the constants σ^A_α for 9,10-anthraquinone were used for 1,4-naphthoquinone, and σ^A_α and σ^A_{meso} for 1,10-anthraquinone were used for 4- and 8-substituted 1,5-naphthoquinones, respectively.

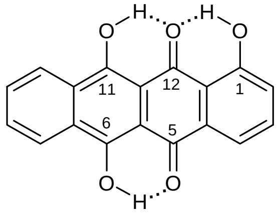
$$\lambda_{max}\ (\text{nm}) = (358.1 \pm 2.0) - (134.23 \pm 1.56)\Sigma\sigma^A; \quad (6)$$
$$N = 4,\ r = 0.99986,\ s = 0.6.$$

Analogous analysis can be performed for naphthacenequinones whose structure constitutes the base of tetracycline antibiotics. The constants σ^A for 1,6,11-trihydroxy-5,12-naphthacenequinone (**XVII**) were selected with no account taken of the unsubstituted benzene ring. The position of the four π_l,π^* bands in the electronic absorption spectrum of **XVII** [12] is described by Eq. (7): λ_{max} 463 nm, 1,6-$(OH^*)_2$-11-OH-5,12; 495 nm, 6,12-$(OH^*)_2$-11-OH-1,5; 519 nm, 5-OH*-11,12-$(OH)_2$-1,6; 530 nm, 5,12-$(OH^*)_2$-11-OH-1,6.

$$\lambda_{max}\ (\text{nm}) = (337.0 \pm 4.4) - (72.41 \pm 1.92)\Sigma\sigma^A; \quad (7)$$
$$N = 4,\ r = 0.9993,\ s = 1.4.$$



XVI



XVII

The data given in the present article indicate that the structure of hydroxy-substituted quinones cannot be represented by a single formula. These compounds exist as equilibrium mixtures of tautomers and conformers, whose composition depends on the conditions, e.g., aggregate state or solvent nature. Variation of solvent or introduction of new substituents not only induces shifts of absorption maxima but also displaces equilibria between different forms. Thus elucidation of factors determining tautomeric and conformational equilibria becomes an important problem in the chemistry of quinones.

Presumably, the proposed concepts implying that tautomeric and confromational equilibria are responsible for the appearance of several π_l,π^* bands in the electronic absorption spectra are applicable not only to anthraquinones and related compounds. These concepts are likely to be general for organic chemistry.

REFERENCES

1. Fain, V.Ya., Zaitsev, B.E., and Ryabov, M.A., *Russ. J. Org. Chem.*, 2005, vol. 41, p. 707.
2. Fain, V.Ya., *9,10-Antrakhinony i ikh primenenie* (9,10-Anthraquinines and Their Aplication), Moscow: Tsentr Fotokhimii Ross. Akad. Nauk, 1999.
3. Fain, V.Ya., *Elektronnye spektry pogloshcheniya i stroenie 9,10-antrakhinonov* (Electronic Absorption Spectra and Structure of 9,10-Anthraquinones), Moscow: Sputnik+, 2003, vols. 1, 2.
4. Fain, V.Ya., Zaitsev, B.E., and Ryabov, M.A., *Russ. J. Gen. Chem.*, 2003, vol. 73, 1595.
5. Fain, V.Ya., *Korrelyatsionnyi analiz elektronnykh spektrov pogloshcheniya* (Correlation Analysis of Electronic Absorption Spectra), Moscow: Sputnik+, 2002, p. 52.
6. Fain, V.Ya., Zaitsev, B.E., and Ryabov, M.A., *Russ. J. Gen. Chem.*, 2003, vol. 73, p. 1925.
7. Fain, V.Ya., *Tablitsy elektronnykh spektrov pogloshcheniya antrakhinona i ego proizvodnykh* (Tabulated Electronic Absorption Spectra of Anthraquinone and Its Derivatives), Leningrad: Khimiya, 1970.
8. Meek, D.B., *J. Chem. Soc.*, 1917, vol. 111, p. 969.
9. Brockmann, H., Boldt, P., and Niemeyer, J., *Chem. Ber.*, 1963, vol. 96, p. 1356.
10. Anoshin, A.N., Val'kova, G.A., Gastilovich, E.A., Klimenko, V.G., Kopteva, T.S., Nurmukhametov, R.N., Rodionov, A.N., and Shcheglova, N.A., *Elektronnokolebatel'nye spektry aromaticheskikh soedinenii s geteroatomami* (Electronic–Vibrational Spectra of Heteroatom-Containing Aromatic Compounds), Moscow: Nauka, 1984, p. 82.
11. Singh, I., Ogata, R.T., Moore, R.E., Chang, C.W.J., and Scheuer, P.J., *Tetrahedron*, 1968, vol. 24, p. 6053.
12. Brockmann, H. and Müller, W., *Chem. Ber.*, 1959, vol. 92, p. 1164.