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SOLID-STATE STRUCTURES OF 2-(4-HYDROXYPHENYL)-SUBSTITUTED PHENALENE-1,3-DIONE AND INDAN-1,3-DIONE

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The structure of 2-(4-hydroxyphenyl)-substituted indan-1,3-dione and phenalene-1,3-dione is investigated using a combination of solid-state NMR, single crystal X-ray analyses and quantum chemical calculations. It is shown that 2-(4-hydroxyphenyl)-1,3-indandione exists as a diketo tautomer while 2-(4-hydroxyphenyl)-1,3-phenalenedione exists in the enol form.

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INTRODUCTION

2-(4-Hydroxyphenyl)-substituted phenalene-1,3-dione and 1,3-indandione belong to cyclic 1,3-diketones — an important class of organic compounds. Numerous 2-substituted 1,3-indandiones have been the subject of investigations due to a variety of biological activities. It is well known that radicals are involved in many biological processes [1]. Some of them probably participate in the complex mechanism of inflammation [2]. 2-(4-Hydroxyphenyl)-1,3-indandione is described in the literature [3-10] and is of interest in radical processes [11]. It also exhibits anti-inflammatory activity [10]. The compound has been obtained with a quite high yield (84% [8] and 92% [10]). Since the melting point given in [7] is not in agreement with other literature data [3-6, 8-10] there is a doubt that the compound prepared by these authors has the same structure [8, 10]. As 2-substituted 1,3-indanedione derivatives [12], 2-(4-hydroxy-phenyl)-1,3-indandione can exist in diketo or enol tautomeric forms. However, there is no published data on its structure yet.

Phenalene derivatives are nonbenzenoid aromatic compounds. Many natural and synthetic products containing the phenalene moiety have found practical applications [13]. Phenalene-1,3-dione exists in the enol form of 3-hydroxyphenalenone in the solid state [14] and in a DMSO solution where conversion between two identical enol forms with a free energy of activation of *ca* 14 $\text{kcal}\cdot\text{mol}^{-1}$ is observed [15].

A Perkin condensation of 1,8-naphthalic anhydride and substituted phenylacetic acids, and sodium acetate gave a mixture of 2-phenyl-phenalen-1,3-diones and (Z)-3-phenyl-methylene-1*H*,3*H*-naphthol[1,8-*c*,*d*]pyran-1-ones [16-18]. The latter can be separated and purified by column chromatography and recrystallization [19].

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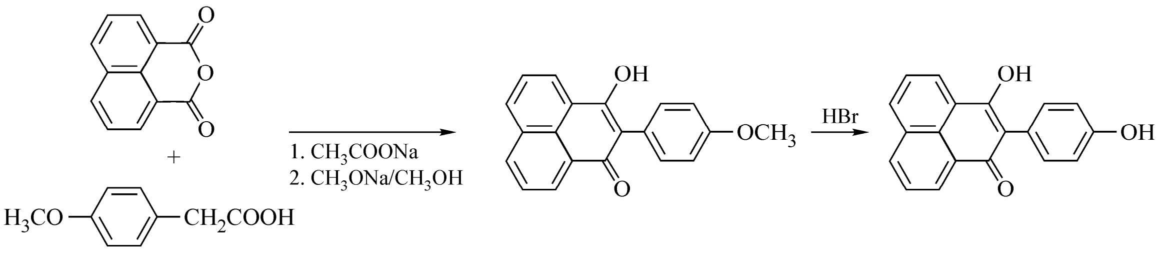
In connection with our interest in tautomerism of cyclic 1,3-diketone derivatives [20-24], the aim of the present study is to elucidate the structure of 2-(4-hydroxyphenyl)-indan-1,3-dione and 2-(4-hydroxyphenyl)-phenalene-1,3-dione. We present a method for the synthesis of the title compound: 2-(4-hydroxyphenyl)-phenalene-1,3-dione. The compound is not described in the literature.

EXPERIMENTAL

Synthesis of 2-(4-hydroxyphenyl)-1,3-indandione. 0.1 mol of phthalide, 0.1 mol of 4-hydroxybenzaldehyde, and 50 ml of ethyl acetate were mixed in a three-neck round-bottom flask fitted with an electric mixer, Allihn condenser, and dropping funnel until the formation of a homogeneous solution. After that, a solution of sodium methylate (prepared from 10.6 g metallic sodium and 150 ml methanol) was added in small portions. The mixture was refluxed for 1 h. The methanol was distilled and the residue was poured into 1 liter of water. After filtering, the filtrate was treated with charcoal and filtered again. Thus obtained filtrate was acidified with HCI till pH 5-6. The precipitate formed was separated and recrystallized from ethanol. Yield: 65%, m.p. 173-174°C.

Synthesis of 2-(4-hydroxyphenyl)-3-hydroxyphenalen-1-one. 0.01 mol of 1,8-naphthalic anhydride, 0.03 mol of 4-methoxyphenylacetic acid, and 0.15 mol of anhydrous sodium acetate were heated at 230-240°C for 3 h. The mixture was cooled down to 50°C and 100 ml of 3% sodium methylate were added. The reaction mixture was refluxed for half an hour. Aqueous 5% sodium acetate was added to the cooled mixture which was then filtered. The filtrate was acidified with glacial acetic acid to pH = 2. Yield of 2-(4-methoxyphenyl)-3-hydroxyphenalen-1-one: 93%; m.p. 231-232°C; $R_f = 0.61$ (benzene:ethanol = 5:1) and 0.40 (ethyl acetate:petroleum ether = 1:2). Elemental analysis, calcd. C 79.46%, H 4.67%; found C 79.26%, H 4.53%.

0.01 mol of 2-(4-methoxyphenyl)-3-hydroxyphenalen-1-one, 20 ml glacial acetic acid, and 50 ml of 48% HBr were refluxed for 3 h. Then the mixture was diluted with 250 ml of hot water. After cooling the solution was filtered and the residue formed of 2-(4-hydroxyphenyl)-3-hydroxyphenalen-1-one was dried and recrystallized from benzene. Yield: 91%, m.p. 278-279°C, $R_f = 0.66$ (benzene:ethanol = 5:1) and 0.43 (ethyl acetate:petroleum ether = 1:2). Elemental analysis: calcd. C 79.16%, H 4.20%; found C 79.05%, H 4.08%.



Scheme 1

All chemicals used were purchased from Merck, Fluka, and Aldrich with p.a. purity. The melting points were determined with a Koffler apparatus. The elemental analysis data were obtained with an automatic analyzer Carlo Erba 1106. The purity of the analyzed compounds was checked by thin layer chromatography on Kieselgel 60 F_{254}, 0.2 mm Merck plates.

COMPUTATIONAL DETAILS

The calculations were carried out using the GAMESS quantum chemistry package [25]. The geometries of both tautomeric forms **A** and **B** of 2-(4-hydroxyphenyl)-1,3-indandione (**1**) and 2-(4-hydroxyphenyl)-phenalene-1,3-dione (**2**) (Fig. 1) were located at three different computational levels: Hartree–Fock (HF), DFT (the hybrid B3LYP functional which combines the three-parameter exchange functional of Becke [26] with the LYP correlation one [27]), and second order

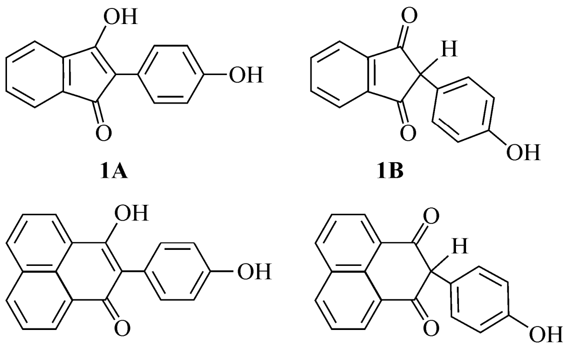


Fig. 1. Structures of enol (**A**) and keto (**B**) tautomeric forms of 2-(4-hydroxyphenyl)-1,3-indandione (**1**) and 2-(4-hydroxyphenyl)-1,3-phenalenedione (**2**).

Möller–Plesset perturbation theory (MP2) [28] using the 6-31G(*d*,*p*) basis set without symmetry constraints by the gradient procedure. The default gradient convergence threshold (1×10^{-4} Hartree Bohr^{-1}) was used. Frequency calculations at the same level of theory were carried out to determine whether the optimized structures were local minima on the potential energy surface. The values of the enthalpies and Gibbs free energies were also calculated.

The NMR chemical shieldings of the tautomeric forms of compounds were calculated at the B3LYP/6-31+G(*d*,*p*) level using the GIAO approach [29, 30] and MP2/6-31G(*d*,*p*) optimized geometry. In order to compare to the experimental data the calculated absolute shieldings for carbon atoms were transformed to chemical shifts using the reference compound tetramethylsilane, $Si(CH_3)_4$: $\delta = \delta_{calc}(ref) - \delta_{calc}$. Both $\delta_{calc}(ref)$ and δ_{calc} were evaluated at the same computational level. All NMR calculations were carried out using Gaussian 09 [31].

STRUCTURAL DETERMINATION

High resolution mass spectrometry. Electrospray ionization spectra were recorded on a Bruker-Daltronics® BioTof mass spectrometer in positive (ESI+) ion mode. Both compounds were dissolved in acetonitrile with traces of Na cations. The observed masses ($M+Na^+$) were calibrated (internal) with Poly Propylene Glycol (PPG).

Single crystal X-ray analysis. In order to prepare high quality crystals suitable for single crystal X-ray data collection few crystals of compounds **1** and **2** were dissolved in different vials in a minimum amount of acetone. Both vials were capped with rubber septa stuck with a needle and left undisturbed in the hood. Compound **1** formed plate-like colorless crystals, while compound **2** gave orange parallelepipeds.

A Bruker Apex Duo diffractometer with an Apex 2 CCD area detector and IμS Cu X-ray radiation was used to collect the data at $T = 100$ K. Both structures were processed with the Apex 2 v2010.9-1 software package (SAINT v. 7.68A, XSHELL v. 6.3.1). A direct method was used to solve the structures after multi-scan absorption corrections. Details of the data collection and refinement are given in Table 1. Crystallographic data have been deposited with the Cambridge Crystallographic Database CCDC 887704 and 887705.

Solid state NMR. The solid-state ^{13}C cross-polarization (CP) magic angle spinning (MAS) spectrum was recorded on a Bruker DRX-400 spectrometer at 100.61 MHz. The powder sample was spun at 10 kHz in a 4 mm ZrO_2 rotor (contact time of 2 ms, repetition time of 6 s) and 600 scans were accumulated. For assigning the quaternary carbon atoms the dipolar diphased spectra were recorded with a 50 μs pre-acquisition delay. ^{13}C chemical shifts were calibrated indirectly through the glycine CO signal recorded at 176.0 ppm, relative to TMS.

TABLE 1. Crystal and Refinement Parameters for Compounds **1** and **2**

Parameters	**1B**	**2A**
Formula	$2(C_{15}H_{10}O_3)\cdot C_3H_6O$	$C_{19}H_{12}O_3\cdot 2(H_2O)$
FW	534.55	324.32
Cryst. size, mm	0.17×0.12×0.03	0.13×0.12×0.09
Cryst. system	Monoclinic	Triclinic
Space group, *Z*	*Pn*, 2	*P*-1, 2
a, *b*, *c*, Å	11.4609(8), 5.2394(4), 21.3174(15)	7.5371(3), 10.0918(4), 10.1331(3)
α, β, γ, deg	90, 94.332(3), 90	98.183(2), 99.006(2), 101.462(2)
V, Å^3	1276.42(16)	734.00(5)
ρ_{calc}, g/cm^3	1.391	1.467
μ, cm^{-1}	0.801	0.882
Radiation type	Cu	Cu
$F(000)$	560	340
N of measured refl./indep. refl.	13541/4105	8929/2518
N of refl. ($I \geq 2\sigma$)	4007	2352
Resolution, Å	0.84	0.84
$R1/wR2$ $(I \geq 2\sigma)^a$, %	2.88/7.93	4.32/11.79
$R1/wR2$ (all data), %	2.93/7.98	4.51/11.97

$^a R1 = \Sigma||F_0| - |F_c||/\Sigma||F_0|$, $wR2 = [\Sigma w[(F_0)^2 - (F_c)^2]^2/\Sigma w(F_0^2)^2]^{1/2}$ for $F_0^2 > 2\sigma(F_0^2)$, $w = [\sigma^2(F_0)^2 + (AP)^2 + BP]^{-1}$, where $P = [(F_0)^2 + (F_c)^2/3$ and A, B coefficient for both compounds as follow: **1B**, $A(B) = 0.0420$ (0.2271); **2A**, $A(B) = 0.0677$ (0.2368).

RESULTS AND DISCUSSION

Structure of 2-(4-hydroxyphenyl)-1,3-indandione. Like all 1,3-diketones, 2-(4-hydroxyphenyl)-substituted phenalene-1,3-dione and 1,3-indandione can exist in two tautomeric forms shown in Fig. 1. In order to estimate the energy difference between tautomers of compounds **1** and **2** we have performed quantum chemical calculations at HF, MP2, and DFT levels of theory. The calculated values are presented in Table 2. Our calculations predict the tautomer **B** of 2-(4-hydroxyphenyl)-1,3-indandione as more stable at all levels of theory. The relative enthalpies (ΔH_0) range from 4.10 kcal·mol^{-1} to 8.57 kcal·mol^{-1} depending on the level of the calculation. Inclusion of entropy corrections in the relative stabilities systematically increases the differences in comparison with the ΔH_0 results (5.19-9.84 kcal·mol^{-1}). Such substantial energy differences make the existence of the tautomer **A** unlikely.

These results are in consent with the data obtained from ^{13}C CPMAS NMR for 2-(4-hydroxyphenyl)-1,3-indandione, **1** (Fig. 2). Two carbonyl signals at 204.1 ppm and 199.6 ppm, one phenolic signal at 158.0 ppm and a signal at 61.1 ppm for aliphatic carbon indicate the presence of diketo tautomer **1B** (Fig. 1) in the solid state. The B3LYP/6-31+G(*d*,*p*) calculated carbon chemical shifts for tautomers **1A** and **1B**, and experimental ^{13}C chemical shifts are presented in Table 3. There is very good agreement between the experimental values and calculated ones for tautomer **1B**.

Compound **1** crystalizes in a monoclinic crystal system (Table 1). Each cell contains four molecules of **1B** and two molecules of acetone, as a co-crystallized solvent (Fig. 3). All bond distances in **1B** (Fig. 3) are in very good agreement with the literature [32] and the quantum chemically calculated bond distances presented in Table 4. The molecule has one C(*sp*^{3}) atom which forms three C(*sp*^{3})–C(*sp*^{2}) bonds with an average length of 1.52 Å and one C–H bond. The two C(*sp*^{2})–C(*sp*^{2}) single bonds are 1.48 Å and 1.49 Å, and all aromatic bonds are in the range of 1.39 Å to 1.40 Å. The oxygen atoms form two C(*sp*^{2})=O bonds and one C(*sp*^{2})–O with an average length of 1.22 Å and 1.37 Å respectively. Each **1B** molecule has two strong hydrogen bond interactions with the neighboring hydroxyl group and one carbonyl group. The observed H…acceptor

TABLE 2. Total Energies (E_T), Enthalpies at 0 K (H_0) and Gibbs Free Energies at 298 K (G_{298}, au) Calculated at Different Computational Levels for Both Tautomeric Forms of 2-(4-Hydroxyphenyl)-1,3-indandione, **1**, and 2-(4-Hydroxyphenyl)-phenalene-1,3-dione, **2**, Shown in Fig. 1, and Relative Total Energies (ΔE_T), Relative Enthalpies at 0 K (ΔH_0) and Relative Gibbs Free Energies at 298 K (ΔG_{298}, kcal·mol^{-1})

Compound	Computational level					
	HF/6-31G(*d*,*p*)		B3LYP/6-31G(*d*,*p*)		MP2/6-31G(*d*,*p*)	
	E_T	ΔE_T	E_T	ΔE_T	E_T	ΔE_T
1A	–798.458938	8.21	–803.299091	3.57	–800.935696	6.29
1B	–798.472024	0.00	–803.304791	0.00	–800.945715	0.00
2A	–951.131163	0.00	–956.964019	0.00	–954.131034	0.00
2B	–951.129082	1.31	–956.954891	5.73	–954.127412	2.27
	H_0	ΔH_0	H_0	ΔH_0	H_0	ΔH_0
1A	–798.230757	8.57	–803.086544	4.10	–800.723382	6.32
1B	–798.244413	0.00	–803.093083	0.00	–800.733457	0.00
2A	–950.852034	0.00	–956.703896	0.00	–953.869185	0.00
2B	–950.850339	1.06	–956.695414	5.32	–953.866903	1.43
	G_{298}	ΔG_{298}	G_{298}	ΔG_{298}	G_{298}	ΔG_{298}
1A	–798.271374	9.84	–803.127477	5.19	–800.765004	7.08
1B	–798.287056	0.00	–803.135748	0.00	–800.776291	0.00
2A	–950.895499	0.01	–956.747608	0.00	–953.913332	0.00
2B	–950.895521	0.00	–956.740643	4.37	–953.913006	0.20

distances are 1.96 Å and 1.90 Å and donor…H…acceptor angles are 169.6° and 174.6° respectively. The second carbonyl group is involved in a much weaker interaction with a hydrogen atom from a phenyl ring. The solvent molecule is not involved in any hydrogen bond interactions.

The chemical shifts measured by MAS NMR reflect conformations that are frozen in solid phase, as well as the intermolecular interactions (hydrogen bonding and crystal packing effects). The decrease of shielding for carbonyl carbons involved in the hydrogen bond and changes in shielding for the carbon-bearing hydroxyl group and its neighbors are usually observed in solid-state ^{13}C spectra, in comparison to the spectra in solutions.

Nonequivalence of the two carbonyl groups in the MAS spectrum (Fig. 2) indicates that one of them (C9=O) is engaged in the intermolecular hydrogen bond. The difference between the calculated and experimental chemical shifts for C9 amounts ca. 4 ppm. A similar difference for carbon C15 is probably also caused by the hydrogen bond formation. The locked and planar conformation of the C15–OH group with the OH hydrogen atom directed towards C16 should result in the increase in its shielding (and the decrease in C14 shielding). The same experimental chemical shifts of C16 and C14 suggest the out-of-plane orientation of this group in the crystal structure in agreement with X-ray diffraction (XRD).

It is worth mentioning that the solid studied by MAS NMR does not contain the same crystallite as that studied by XRD, since no resonances of acetone appeared in the spectrum.

In order to fully characterize compound **1**, high resolution ESI-MS was performed and the results are shown in red color in Fig. 4. The peaks at 499.1153, 500.1205, and 501.1231 are assigned to two neutral molecules of **1** ionized with a sodium cation. The characteristic peaks of only one molecule of **1** ionized with a sodium cation were also observed at 261.0524, 262.0564, and 263.0622, but they are not shown in the picture. Two strong peaks at 497.1006 and 498.1047 were observed in addition to the two sets of peaks described above. A possible explanation of these peaks is a dimer of 2-(4-hydroxy-phenyl)-1,3-indandione. The theoretical mass spectroscopy pattern of such a dimer ionized with Na$^+$ and its structure are shown in black in Fig. 4. The calculated mass spectroscopy error between experiment and theory is 2 ppm, which convinced us that our assumption is correct. Neilands and Romanovskii [8] have suggested that in dioxane, alcohol and acetone solution, 2-(4-hydroxyphenyl)-1,3-indandione can form a stable dimer.

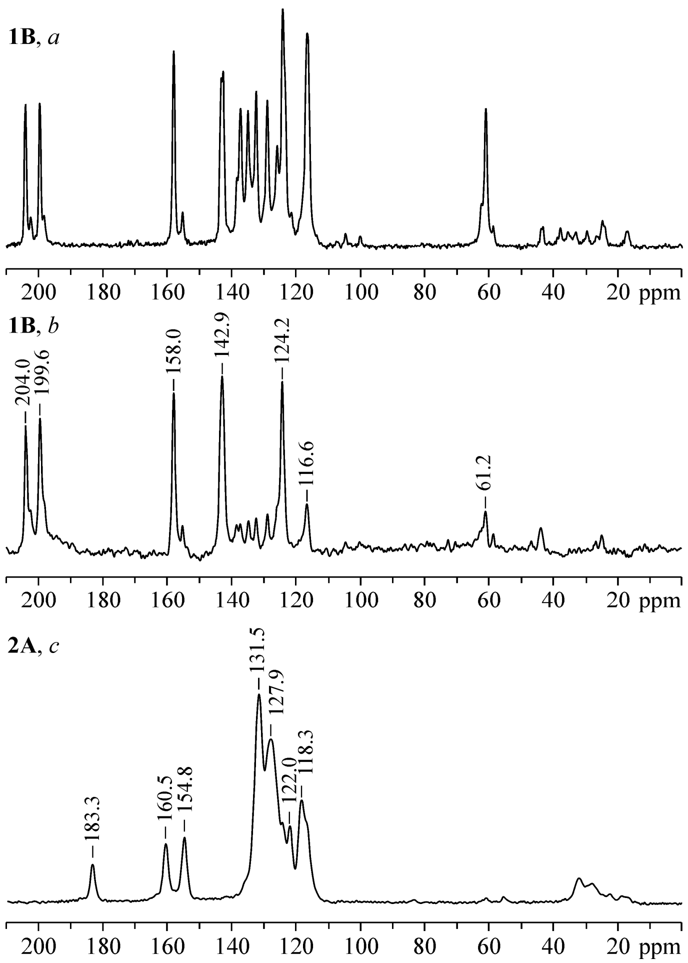


Fig. 2. Solid-state ^{13}C CPMAS NMR spectra of 2-(4-hydroxophenyl)-1,3-indandione (**1B**): *a*) standard, *b*) recorded with dipolar dephased pulse sequence and *c*) standard spectrum of 2-(4-hydroxyphenyl)-3-hydroxyphenalene-1-one (**2A**). Small signals below 60 ppm are rotational side-bands.

TABLE 3. B3LYP/6-31+G(*d,p*) GIAO Calculated Chemical Shifts (δ_{calc}, ppm) for the Tautomers **A** and **B** of 2-(4-Hydroxyphenyl)-1,3-indandione **1** and 2-(4-Hydroxyphenyl)-phenalenedione **2**. The ^{13}C CPMAS NMR Chemical Shifts (δ_{exp}, ppm) were Measured at 100.1 MHz (DSX Bruker-400). The Atom Numbering is Shown in Figs. 3 and 5

Compound **1**				Compound **2**			
Carbon	**1A**	**1B**		Carbon	**2A**	**2B**	
	δ_{calc}	δ_{calc}	δ_{exp}		δ_{calc}	δ_{calc}	δ_{exp}
1	2	3	4	5	6	7	8
1	119.44	122.05	124.2	1	130.04	132.15	131.5
2	127.77	132.15	137.0	2	130.55	131.67	131.1
3	129.56	132.15	135.0	3	125.57	132.04	124.2
4	115.99	122.05	125.9	4	124.38	129.42	124.2
5	138.99	143.05	142.9	5	125.52	128.52	127.9
6	132.43	143.06	142.9	6	123.39	124.07	124.2
7	192.05	199.92	199.6	7	131.35	132.06	131.5
8	111.95	64.30	61.1	8	124.23	124.11	125.9
9	170.27	199.92	204.1	9	129.56	128.70	131.5

TABLE 3. (Continued)

1	2	3	4	5	6	7	8
12	122.55	130.05	124.2	10	128.89	129.14	127.5
13	131.17	130.56	132.4	11	178.91	194.43	183.3
14	115.98	114.17	116.6	12	119.09	74.85	118.8
15	154.14	154.11	158.0	13	157.42	194.68	160.5
16	110.05	110.98	116.6	16	123.93	128.07	122.0
17	122.52	124.25	129.0	17	125.84	128.98	127.9
				18	109.28	111.44	116.7
				19	154.93	154.41	154.8
				20	115.27	113.33	118.3
				21	134.95	125.28	131.5

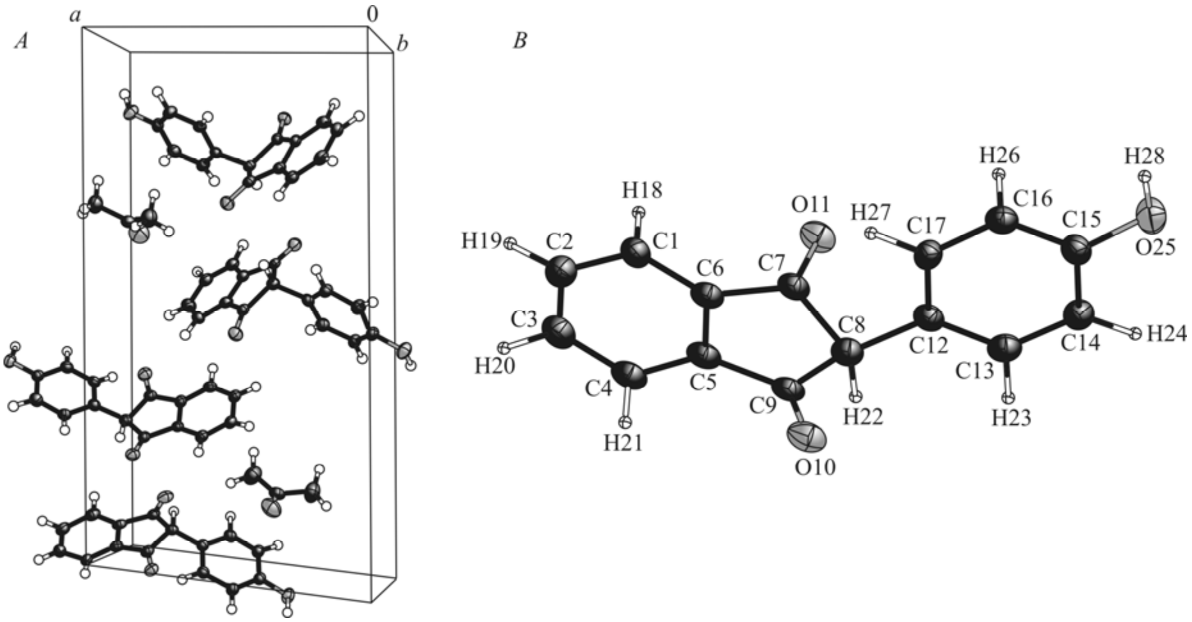


Fig. 3. *A*) Cell packing of 2-(4-hydroxyphenyl)-1,3-indandione. The compound crystalized with 4 main molecules and 2 solvent molecules (acetone) per cell. *B*) Crystal structure of 2-(4-hydroxyphenyl)-1,3-indandione, **1B**. All thermal ellipsoids are presented with 50% probability.

Structure of 2-(4-hydroxyphenyl)-3-hydroxyphenalen-1-one. The B3LYP calculated enthalpy difference between tautomers **2A** and **2B** is quite large (5.32 kcal·mol^{-1}) while the enthalpy differrences, calculated at HF and MP2 levels are 1.06 kcal·mol^{-1} and 1.43 kcal·mol^{-1} respectively. The free energy differences between both tautomers decrease by about 1 kcal·mol^{-1} and as a result both tautomers become very close in energy at the MP2 level (0.20 kcal·mol^{-1}) and practically isoenergetic at the HF level (Table 2). According to the calculations at the B3LYP/6-31G(*d*,*p*) level of theory enol tautomer **2A** (2-(4-hydroxyphenyl)-3-hydroxy-phenalene-1-one) is more stable and diketo tautomer **2B** is higher by 4.37 kcal·mol^{-1} in energy.

The B3LYP/6-31+G(*d*,*p*) calculated carbon chemical shifts for both tautomers of 2-(4-hydroxyphenyl)-1,3-phenalenedione and selected experimental chemical shifts of **2** are presented in Table 3. Comparing the experimental and calculated carbon chemical shifts the existence of the enol form of **2A** can be proposed: one carbonyl signal at 183.3 ppm (C11) and two phenolic signals at 160.5 ppm (C13) and 154.8 ppm (C19) (Fig. 5).

Compound **2** crystalized in a triclinic crystal system (Table 1). Each cell consists of two molecules of **2A** and four molecules of water as a co-crystallized solvent (Fig. 5). All C atoms in **2A** are *sp*^{2}-hybridized and form 2 types of bonds

TABLE 4. Selected X-Ray and Calculated (MP2/6-31G(*d*,*p*) and B3LYP/6-31G(*d*,*p*)) Bond Distances (Å) and Dihedral Angles (deg) for **1B** (Fig. 3) and **2A** (Fig. 5). The Atom Numberings are Given in the Respective Figures

Bond	exptl	MP2	B3LYP	Bond	exptl	MP2	B3LYP	Bond	exptl	MP2	B3LYP
1B				**2A**							
C1–C2	1.387(3)	1.395	1.394	C1–C2	1.413(2)	1.419	1.421	C19–C20	1.388(2)	1.396	1.401
C2–C3	1.391(3	1.407	1.407	C2–C3	1.418(2)	1.427	1.427	C20–C21	1.384(2)	1.396	1.388
C3–C4	1.381(3)	1.395	1.394	C3–C4	1.419(2)	1.423	1.426	C16–C21	1.396(2)	1.406	1.409
C4–C5	1.400(3)	1.395	1.396	C4–C5	1.383(2)	1.389	1.388	C19–O31	1.370(2)	1.371	1.365
C5–C6	1.391(3)	1.400	1.399	C5–C6	1.404(2)	1.409	1.411	O31–H34	0.99(3)	0.966	0.966
C1–C6	1.400(3)	1.395	1.396	C1–C6	1.366(2)	1.381	1.378				
C5–C9	1.479(3)	1.487	1.490	C2–C7	1.414(2)	1.417	1.419	Angle			
C6–C7	1.480(3)	1.487	1.490	C7–C8	1.370(2)	1.383	1.380	C11–C12–C16–C21	64.6	51.4	49.9
C7–C8	1.536(3)	1.535	1.548	C8–C9	1.399(2)	1.407	1.409				
C8–C9	1.536(3)	1.536	1.548	C9–C10	1.382(2)	1.387	1.385				
C9–O10	1.206(2)	1.225	1.214	C3–C10	1.418(2)	1.417	1.419				
C7–O11	1.217(2)	1.225	1.214	C10–C11	1.473(2)	1.489	1.493				
C8–C12	1.512(3)	1.508	1.512	C11–C12	1.431(2)	1.469	1.474				
C12–C13	1.390(3)	1.396	1.397	C12–C13	1.392(2)	1.372	1.373				
C13–C14	1.390(3)	1.395	1.394	C4–C13	1.461(2)	1.455	1.459				
C14–C15	1.390(3)	1.396	1.397	C11–O14	1.273(2)	1.241	1.234				
C15–C16	1.383(3)	1.398	1.400	C13–O15	1.319(2)	1.362	1.356				
C16–C17	1.385(3)	1.390	1.389	O15–H28	0.78(4)	0.972	0.972				
C12–C17	1.391(3)	1.404	1.404	C12–C16	1.489(2)	1.476	1.486				
C15–O25	1.373(2)	1.372	1.366	C16–C17	1.396(2)	1.405	1.406				
O25–H28	0.91(3)	0.966	0.966	C17–C18	1.388(2)	1.389	1.396				
C8–H22	1.00(2)	1.093	1.099	C18–C19	1.387(2)	1.400	1.396				

between themselves: aromatic, with bond lengths of 1.37-1.42 Å, and C(sp^2)–C(sp^2) single bonds with an average bond distance of 1.47 Å. In contrast to **1B**, **2A** has two hydroxyl groups and only one carbonyl group. The C19–O31 single bond is 1.370(2) Å, while C13–O15 is 1.319(2) Å, which appears to be a little shorter. On the other hand, the C11=O14 double bond is 1.273(2) Å, which is slightly longer than that expected for the C(sp^2)=O double bond [32]. Unlike the packing in compound **1B**, here the co-crystalized four water molecules are all involved in a 3D hydrogen bonding network. Each of the two hydroxyl groups and the carbonyl group of **2A** form hydrogen bonds with two water molecules, but there is no direct intermolecular interaction between the molecules of **2A**.

2-(4-Hydroxyphenyl)-3-hydroxyphenalene-1-one has a sterically hindered phenolic fragment. The MP2- and B3LYP-calculated dihedral angles between the phenol ring and the phenalene moiety are 51.4° and 49.9° respectively (Table 4).

Deshielding effects observed in the experimental chemical shifts in comparison to the theoretical values suggest that C11=O carbonyl ($\delta_{\mathrm{exp}} - \delta_{\mathrm{calc}} = 4.4$ ppm) and C13–OH (3 ppm) groups form intermolecular hydrogen bonds. The C13–OH group is directed to C12 (a slight increase in shielding, 0.3 ppm). The orientation of C19–OH to C18 should result in the increase in shielding; a large deshielding effect $\delta_{\mathrm{exp}} - \delta_{\mathrm{calc}} = 7.5$ ppm for C18 carbon is observed instead. The difference can be partially explained by intermolecular interactions (two water molecules in the neighborhood) in the solid phase of **2**, and by the twisting of the hydroxyl group out of the aromatic ring plane. The twisted orientation of the phenyl group influences the chemical shifts of C12, C16 and two C17, C21 carbon atoms, next to the linkage. Broad lines in the spectrum of **2** (Fig. 2*c*) suggest that the studied solid is amorphous and may contain some disordered water molecules.

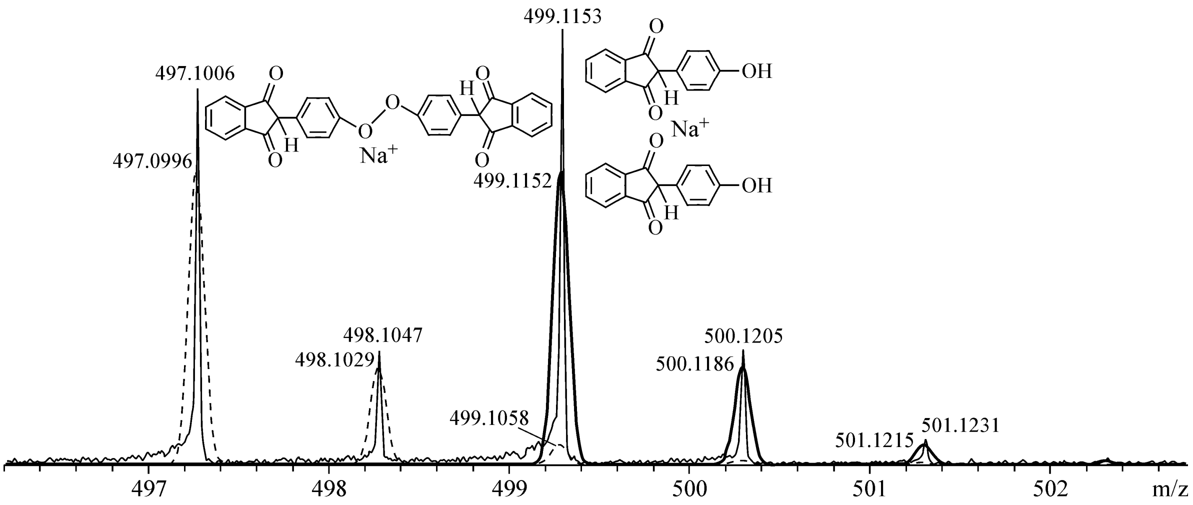


Fig. 4. High resolution ESI+ mass spectroscopy analyze of **1**: —— is experiment, ----- is the simulated pattern of a dimer ionized by Na$^+$, —— is the simulated pattern of two molecules of **1** ionized by one Na$^+$.

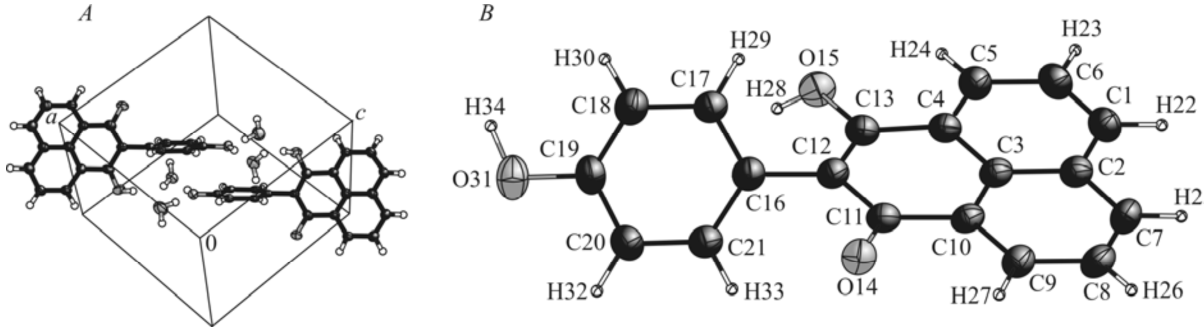


Fig. 5. *A*) Cell packing of 2-(4-hydroxyphenyl)-3-hydroxy-phenale-1-one. The compound crystalized with 2 main molecules and 4 solvent molecules (water) per cell. *B*) Crystal structure of 2-(4-hydroxyphenyl)-3-hydroxyphenale-1-one, **2A**. All thermal ellipsoids are presented with 50% probability.

We performed a high resolution ESI-MS analysis of **2** in acetonitrile, similarly to that of compound **1**. The characteristic peaks of one molecule of **2** ionized with a sodium cation and two molecules of **2** plus Na$^+$ are observed at 311.0679, 312.0704, 313.0809, and at 599.1474, 600.1511, 601.1539 respectively.

CONCLUSIONS

The calculated energy differences between the tautomeric forms of compounds **1** and **2** are sensitive to the level of theory used and the inclusion of entropy corrections. For 2-(4-hydroxyphenyl)-1,3-indandione, the diketo tautomer **B** is calculated to be more stable. Solid-state NMR and X-ray crystallographic results suggest that this tautomeric form is preferred.

In the case of 2-(4-hydroxyphenyl)-substituted phenalene-1,3-dione, the inclusion of entropy corrections makes both tautomers isoenergetic at HF and MP2 levels and only at the DFT level the enol form **A** is predicted to be more stable. The good correspondence between the GIAO B3LYP calculated chemical shifts of this tautomeric forms and the experimentally determined chemical shifts indicates that for compound **2** the enol form is the preferred one. This finding is confirmed by X-ray analysis.

Solid-state NMR enabled us to distinguish which tautomeric form exists in the solid phase, as well as to assess the intermolecular hydrogen bonds in the crystal.

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