

# The Molecular and Crystal Structures of Galvinol Derivatives

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Galvinols are interesting, sterically hindered compounds that serve as precursors for the generation of stable galvinoxyl radicals. In order to elucidate their basic structural chemistry and the influence of steric effects on their conformation a comparative analysis of several galvinol derivatives was undertaken. The aryl and quinoid subunits could clearly be identified, and substituents at the connecting methine bridge were found to influence the conformation of the molecules. As a result of the sterically hindered residues the molecules pack mainly through weak van der Waals interactions without formation of hydrogen bonds. The observation of different crystal forms and packing for galvinols and their conformational flexibility will impact current solid-state applications and provides unambiguous structural data for theoretical calculations.

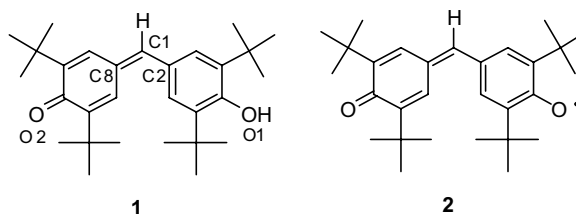
**Key words:** Galvinols, Galvinoxyl Radical, Quinones, Crystal Structure

## Introduction

Galvinol **1** and its radical derivative galvinoxyl **2** have been known and studied for a long time [1, 2]. This is related to the excellent stability of the radical **2** [2], the usefulness of sterically hindered radicals and parent compounds [3], their conducting properties [4], and their chemical reactivity [5]. They are prime candidates for the generation of stable radicals and their derivatives. In a structural sense, derivatives of these compounds are of interest as sterically hindered compounds with hydrogen bond donor and acceptor groups which should show distinctly different packing arrangements from those of unhindered compounds. Despite their application potential no comparative analysis of their structural properties has been performed yet [6–16]. Especially solid-state applications of these compounds require access to unambiguous structural data [17–19]. Thus, following studies on the structural chemistry of sterically hindered aromatic compounds [20] and diaryl species [21], a crystallographic study of a series of galvinol derivatives was undertaken.

## Results and Discussion

An analysis of the available literature reveals only a few structural investigations. The first solid-state



structure of the radical **2** was reported in 1969 by Williams [22]. The molecules have crystallographic 2 ( $C_2$ ) symmetry and thus only averaged structural data for the “two halves” of the molecule were available. Selected structural data are compiled in Table 1. A later determination of a crystal containing both the neutral species and the radical confirmed these results [23]. Only van der Waals-type contacts were found in the crystal structure. A low-resolution structure on **1** was reported in 1999 [24]. Again, the compound crystallized in space group  $C2/c$  with  $Z = 4$  giving only averaged structural data. The same authors also reported the structure of a related tetraethylammonium salt, which indicated slight differences between the two units in the molecule. However, the absence of hydrogen atoms on the oxygen atoms made a clear analysis difficult.

The structure of the diradical derivative **3** revealed distinct structural differences to the monoradical [25].

Table 1. Selected structural data for galvinol derivatives.

Compound	<i>T</i> (K)	Space group	Aryl tilt angle (deg)	C1–C2 (Å)	C1=C8 (Å)	C1–C2–C8 (deg)	C–O1 (Å)	C=O <sub>2</sub> (Å)	Ref.
<b>2</b> (X-ray)	295	<i>C2/c</i>	12	1.42		134	1.27		[22]
<b>2</b> (DFT calc.)			14.3	n. d.	1.408		1.241		[27]
<b>2</b> <sub>0.85</sub> / <b>1</b> <sub>0.15</sub>	203	<i>C2/c</i>	17.3		1.397	135.8	1.224		[23]
<b>3</b>	295	<i>C2/c</i>	55.3	1.436	1.444	121.4	1.242	1.246	[25]
<b>[1]<sup>−</sup></b> <b>[NEt<sub>4</sub>]<sup>+</sup></b> <sup>a</sup>	295	<i>P1</i>	14.1	1.405	1.398	136.4	1.257	1.252	[24]
			12.9	1.435	1.403	135.7	1.289	1.246	
<b>1</b>	295	<i>C2/c</i>	16.8		1.398	140.9	1.264		[24]
<b>1</b>	123	<i>Pbca</i>	139.2(1)	1.414(2)	1.302(2)	122.0(1)	1.377(2)	1.212(2)	this work
<b>1</b>	298	<i>Pbca</i>	139.3(2)	1.417(3)	1.304(3)	122.4(2)	1.375(3)	1.221(3)	this work
<b>5</b>	123	<i>P1</i>	52.4(2)	1.482(3)	1.378(3)	122.6(2)	1.376(3)	1.233(3)	this work
<b>6</b>	90	<i>P2<sub>1</sub>/c</i>	92.7(1)	1.496(2)	1.373(2)	118.3(1)	1.388(2)	1.242(2)	this work
<b>7</b>	293	<i>P1</i>	119.5(2)	1.492(3)	1.377(3)	120.7(2)	1.382(3)	1.229(2)	this work
<b>8<sup>b</sup></b>	150	<i>P1</i>	50.9(3)	1.486(4)	1.380(4)	122.7(3)	1.381(4)	1.230(4)	this work
			134.0(3)	1.489(4)	1.384(4)	121.0(3)	1.368(4)	1.240(4)	
<b>4</b>	158	<i>C2/c</i>	56.4	1.493	1.385	120.2	1.385	1.237	[26]

<sup>a</sup> Two crystallographically independent molecules; <sup>b</sup> structural data given for each “half” of the molecule.

Compound **4** was the first example of a galvinol derivative where the –OH and =O units could clearly be distinguished in the crystal [26]. Nevertheless, a closer investigation of the structural chemistry of this intriguing class of compounds requires a series of closely related galvinol derivatives. Having such a series at hand it was now possible to investigate the influence of substituents on the structural chemistry in more detail.

First, crystallization of **1** from methylene chloride/methanol gave orthorhombic crystals of space group *Pbca*. Structure determinations were performed at 123 K and at room temperature. The molecular structure determined at 123 K is shown in Fig. 1, and the OH hydrogen atom could clearly be identified. The bond length distribution is clearly nonequivalent in the aryl and quinoid system. The molecules pack

closely in the crystal with aryl rings facing each other in an overall zig-zag fashion (not shown). The closest intermolecular contact is between H1A and O1 (1.875 Å). No significant differences were found between the structure at 123 K and that at room temperature (not shown).

Using standard low-temperature crystallographic techniques, the single-crystal X-ray structures of compounds **5–8** were determined as well. The molecular structures of **5** and **6** (Fig. 2) are very similar. However, the steric impact of the substituent at the methine bridge is clearly evident. Compared to **1** the angle at the methine bridge (C2–C1–C8) becomes wider with the quinoid and aryl ring in **6** being orthogonal to each

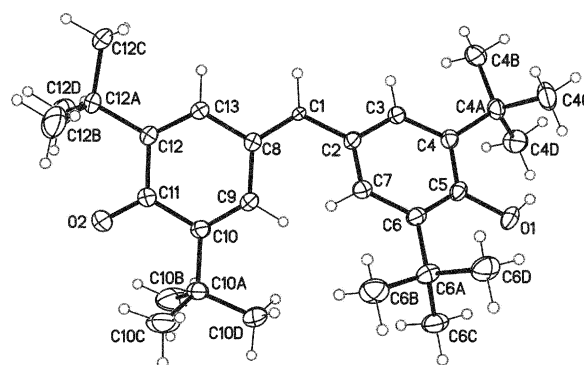
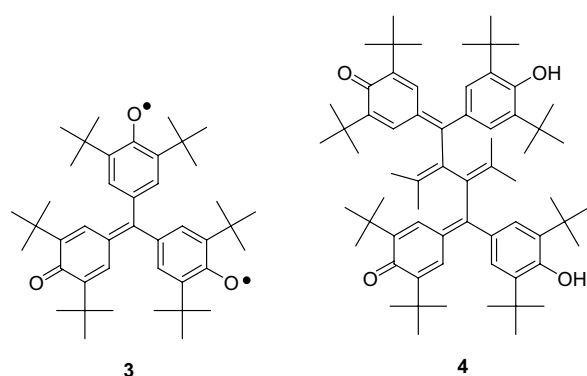
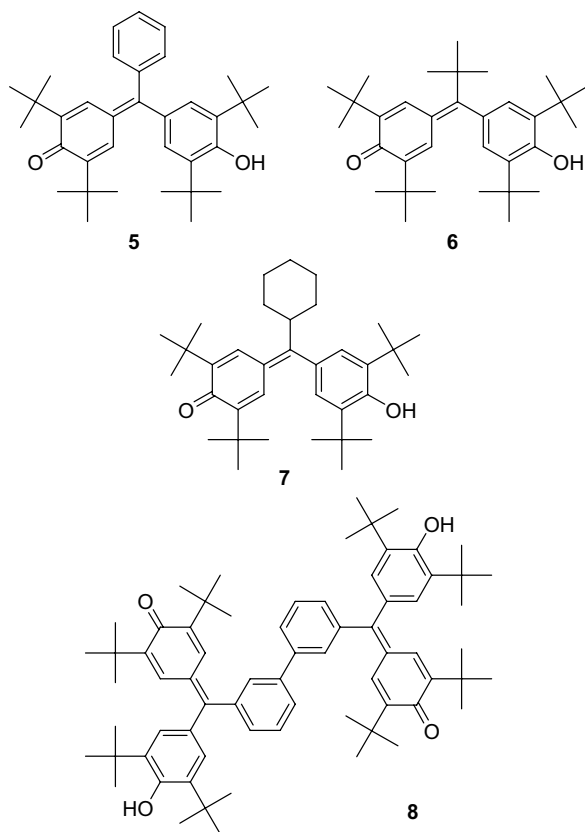


Fig. 1. View of the molecular structure of the orthorhombic form of **1** in the crystal at 123 K; displacement ellipsoids are drawn at the 50% probability level.



other. The C1–C2 and C1–C8 bonds are clearly elongated compared to that in **1** (see data in Table 1).

Very similar results were found for the structure of **7** which is shown in Fig. 3. In terms of steric demand the methine substituent (cyclohexyl) is between that in compounds **5** and **6**. This correlates with the methine bond angle of  $119.5(2)^\circ$ . The cyclohexyl residue adopts a chair conformation with the organic residue in the equatorial position.

The crystal structure of the bisgalvinol derivative **8** is shown in Fig. 4. The molecule crystallizes in the triclinic space group  $P\bar{1}$  with all atoms in the asymmetric unit. In a steric sense the compound is close to compound **5**, *e. g.* with an aryl residue (here a second galvinol unit) as a substituent of the methine bridge. This is clearly evidenced by the structural data. For example, the tilt angles between the aryl and quinoid ring systems are  $50.9(3)^\circ$  and  $134.0(3)^\circ$  in **8** as compared to  $52.4(2)^\circ$  in **5**. Similarly the methine bond angles are  $122.7(3)^\circ$  and  $121.0(3)^\circ$  as compared to  $122.6(2)^\circ$  in **5**.

The basic structural data for the galvinol derivatives are compiled in Table 1. The structural non-equivalence of the residues at the bridging carbon atom are clearly shown by the different C1–C2 and C1–C8 bond lengths. Similarly, the –OH and C=O units are clearly identifiable through the shortened bond lengths in the latter and the identification of the hydroxyl hydrogen atom in several of the structures. The observation of two different crystal forms for **1**, with a significant variation in the conformation about the methine bridge, indicates that despite the sterically hindered structure these systems retain a degree of flexibility. However, the initially reported structure of **1** (space group  $C2/c$ ) is very similar to that of the radical species. The C1–C2–C8 bond angle varies only between  $118.3$  and  $122.7^\circ$  in all other neutral galvinol structures reported here and in ref. [26]. In the reported monoclinic structure for **1** this bond angle is  $134^\circ$ , which casts some doubt on this structure.

Compared to the neutral compound **1** the radical species **2** exhibits a much less distorted conformation while the sterically more hindered bisradical **3** is more distorted. For the structure of the radical a DFT calculation was performed which overall confirmed the solid-state data [27]. Likewise, the steric effects of substituents at the methine bridge are clearly indicated by

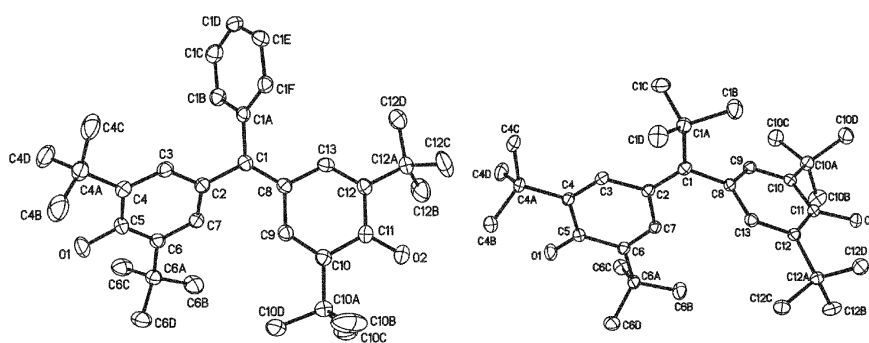


Fig. 2. View of the molecular structure of **5** (left) and **6** (right) in the crystal. Displacement ellipsoids are drawn at the 50% probability level; hydrogen atoms have been omitted for clarity.

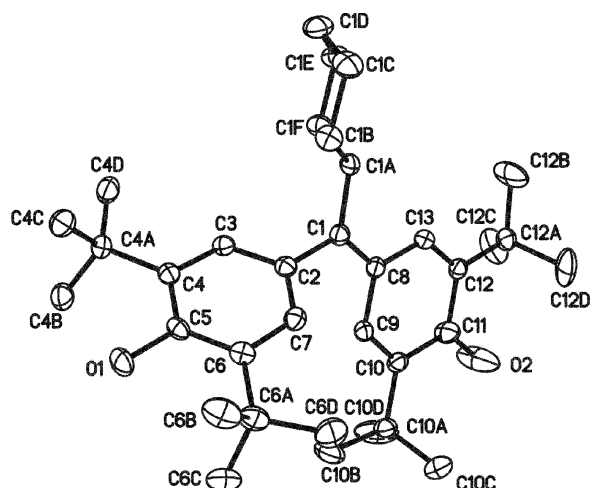


Fig. 3. View of the molecular structure of **7** in the crystal. Displacement ellipsoids are drawn at the 50% probability level; hydrogen atoms have been omitted for clarity.

an increasing twist of the aryl and quinoid residues about the methine bridge. The C1–C2–C8 bond angle and the aryl/quinone tilt angle become progressively larger in the order **1** < **8** ~ **5** < **7** < **6**, e. g. with  $H < \text{aryl} < \text{cyclohexyl} < \text{tert-butyl}$ .

A few other structures on chemically related compounds have been reported. One example results from a reaction at the methine bridge [28], the other from reactions at the double bonds of the cyclohexanone ring [29, 30]. Another possibility to “fix” one of the halves of the molecule is to react the galvinoxyl radical with germynes or stannylenes [31] or with cobalt

derivatives [32]; a few of the derivatives obtained have been characterized. However, these compounds are structurally too unrelated for the present discussion.

As described above, the orthorhombic form of **1** showed no unusual or hydrogen bonding interactions in the crystal. Similarly, no close contacts of hydrogen bonds were found in the crystal packing of the phenyl derivative **5** nor in the cyclohexyl derivative **7** (not shown). Compound **6** crystallizes with a disordered ethanol molecule of solvation. As shown in Fig. 5, the solvate molecules are located in the void between lines of galvinol molecules. Here, the galvinol molecules form polymers where the hydroxyl group of one molecule is hydrogen-bonded to the carbonyl oxygen atom of the next ( $O1 \cdots O2$  2.790 Å,  $H2 \cdots O1$  1.951 Å). No other intra- or intermolecular contacts were found.

Compound **8** crystallized with methylene chloride and methanol molecules of solvation. As shown in Fig. 6 the galvinol molecules form layers with the methylene chloride molecules interspaced between the layers. One of the methanol molecules is hydrogen-bonded to a carbonyl oxygen atom [ $O3S \cdots O2$  2.778 Å,  $H2S$ ]. Other close intermolecular contacts are  $H2S2 \cdots O1$  (2.513 Å) and  $H2S3 \cdots O3$  (2.450 Å). The structural data for the hydrogen bonds in the crystals of **6** and **8** conform with the requirements outlined by Steiner [33].

In conclusion, comparative structural data for a series of closely related galvinol derivatives have been established. The data cast some doubt on an earlier structure of the parent compound **1** and indicate the

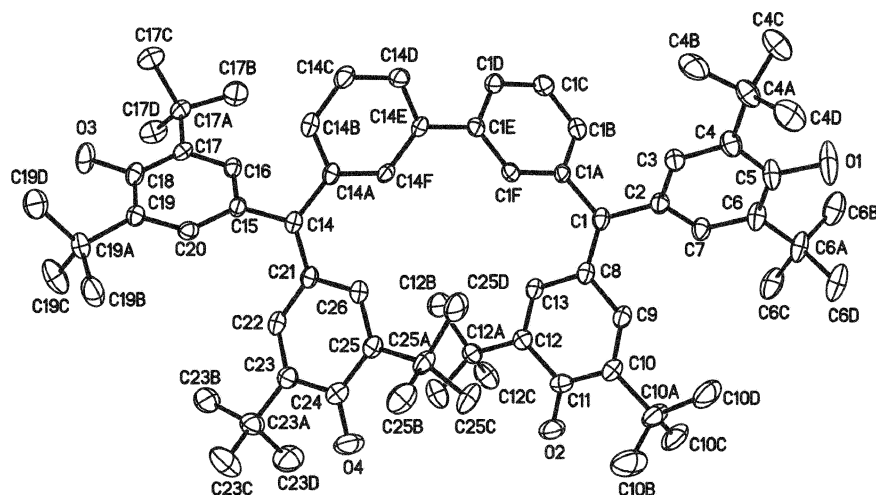


Fig. 4. View of the molecular structure of **8** in the crystal. Displacement ellipsoids are drawn at the 50% probability level; hydrogen atoms have been omitted for clarity.

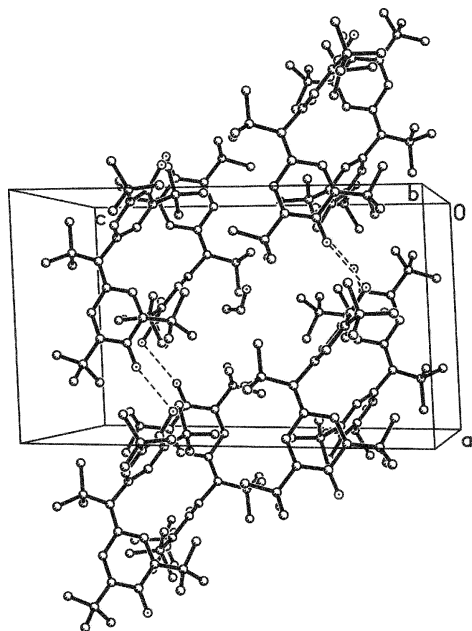


Fig. 5. View of the crystal structure of **6**. Hydrogen atoms have been omitted for clarity. Dashed lines indicate hydrogen bonds.

influence of additional residues on the conformation of the title compound. As a result of the steric hindrance in the compounds and of the presence of hydrocarbon residues shielding the C–O units, most derivatives pack without formation of hydrogen bonds. Only the highly twisted *tert*-butyl derivative **6** forms hydrogen bonds between the galvinol molecules in the solid state. Clear structural differences were found between the structures of the neutral galvinols and the related galvinoxyl radical species.

### Experimental

The compounds were prepared as described before [10, 11]. Growth and handling of crystals followed the concept developed by Hope [34]. The diffraction intensities were corrected for Lorentz and polarization effects. The structures were solved with Direct Methods using the SHELXTL PLUS program system [35] and refined against  $F^2$  with the routine XL from SHELXL-97 using all data [35]. Non-hydrogen atoms were refined with anisotropic parameters. Hydrogen atoms were generally placed into geometrically calculated positions and refined using a riding model. Unless otherwise stated, OH hydrogen atoms were located in difference

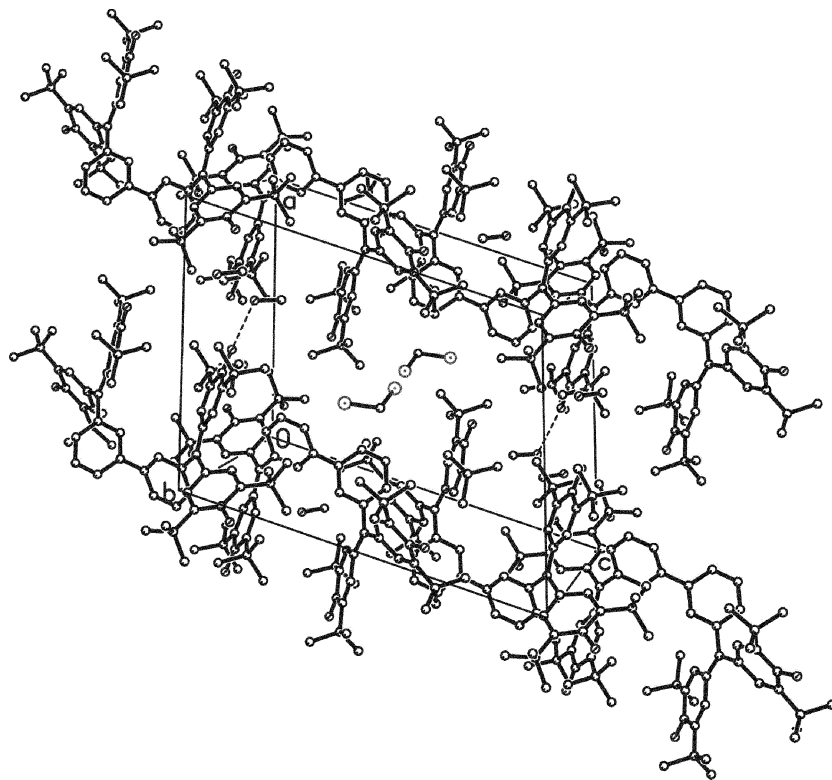


Fig. 6. View of the crystal structure of **8**. Hydrogen atoms have been omitted for clarity. Dashed lines indicate hydrogen bonds.

Table 2. Summary of crystal data, data collection and refinement for the crystal structure determinations.

	<b>1</b>	<b>1</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>
Formula	C <sub>29</sub> H <sub>42</sub> O <sub>2</sub>	C <sub>29</sub> H <sub>42</sub> O <sub>2</sub>	C <sub>35</sub> H <sub>46</sub> O <sub>2</sub>	C <sub>33</sub> H <sub>50</sub> O <sub>2</sub> · 0.5 C <sub>2</sub> H <sub>6</sub> O	C <sub>35</sub> H <sub>52</sub> O <sub>2</sub>	C <sub>70</sub> H <sub>90</sub> O <sub>4</sub> ·CH <sub>2</sub> Cl <sub>2</sub> · 2 CH <sub>3</sub> OH
<i>M<sub>r</sub></i>	422.63	422.63	498.72	501.76	504.77	1144.43
Crystallization	CH <sub>2</sub> Cl <sub>2</sub> -CH <sub>3</sub> OH	CH <sub>2</sub> Cl <sub>2</sub> -CH <sub>3</sub> OH	CH <sub>2</sub> Cl <sub>2</sub> -CH <sub>3</sub> OH	CH <sub>2</sub> Cl <sub>2</sub> -EtOH	CH <sub>2</sub> Cl <sub>2</sub> -CH <sub>3</sub> OH	CH <sub>2</sub> Cl <sub>2</sub> -CH <sub>3</sub> OH
Color, habit	red prism	red block	orange block	yellow block	colorless block	orange prism
Crystal size, mm <sup>3</sup>	0.39 × 0.37 × 0.35	0.18 × 0.12 × 0.09	0.23 × 0.13 × 0.1	0.5 × 0.5 × 0.4	0.4 × 0.4 × 0.15	0.34 × 0.1 × 0.1
Crystal system	orthorhombic	orthorhombic	triclinic	monoclinic	triclinic	triclinic
Space group	<i>Pbca</i>	<i>Pbca</i>	<i>P</i> $\bar{1}$	<i>P</i> 2 <sub>1</sub> / <i>c</i>	<i>P</i> $\bar{1}$	<i>P</i> $\bar{1}$
<i>a</i> , Å	19.2265(10)	19.259(5)	10.372(4)	11.7252(7)	11.3240(19)	14.5724(9)
<i>b</i> , Å	13.9214(7)	13.950(4)	11.083(5)	14.5028(9)	11.971(3)	14.9718(9)
<i>c</i> , Å	19.6042(10)	19.647(7)	14.277(6)	19.0897(12)	14.3144(18)	18.2291(12)
$\alpha$ , deg	90	90	110.660(9)	90	97.621(15)	95.883(2)
$\beta$ , deg	90	90	98.341(9)	92.779(1)	106.819(13)	109.264(1)
$\gamma$ , deg	90	90	95.501(9)	90	116.61(2)	112.045(1)
<i>V</i> , Å <sup>3</sup>	5247.3(5)	5278(3)	1500.0(11)	3242.4(3)	1580.8(5)	3361.5(4)
<i>Z</i>	8	8	2	4	2	2
<i>d</i> <sub>calcd.</sub> , Mg m <sup>-3</sup>	1.07	1.06	1.10	1.03	1.06	1.13
$\mu$ , mm <sup>-1</sup>	0.1	0.5	0.1	0.1	0.1	0.1
$\theta$ <sub>max</sub> , deg	28.35	59.03	25	27.56	25.05	22.84
Radiation	Mo <i>K</i> $\alpha$	Cu <i>K</i> $\alpha$	Mo <i>K</i> $\alpha$	Mo <i>K</i> $\alpha$	Mo <i>K</i> $\alpha$	Mo <i>K</i> $\alpha$
<i>T</i> , K	123	298	123	90	293	150
Refl. coll./indep.	51 097/6556	15 041/3780	12 092/5276	35 160/7488	7073/4756	27 089/11 831
<i>R</i> <sub>int</sub>	0.0367	0.0151	0.0361	0.0294	0.0152	0.0474
Refl. with <i>F</i> > 4.0 $\sigma$ ( <i>F</i> )	5252	3112	3632	6044	3862	7479
No. of ref. parameters	292	292	346	358	346	756
<i>R</i> 1/ <i>wR</i> 2	0.0687/0.1868	0.0508/0.1474	0.0561/0.1222	0.0477/0.1256	0.0463/0.1160	0.0805/0.2065
[ <i>F</i> > 4.0 $\sigma$ ( <i>F</i> )]						
<i>R</i> 1/ <i>wR</i> 2 (all data)	0.0830/0.2009	0.0584/0.1529	0.0881/0.1375	0.0621/0.1377	0.0592/0.1219	0.1257/0.2383
<i>S</i>	1.034	1.082	1.009	1.041	1.052	1.030
$\Delta\rho_{\text{fin}}$ (max.), e Å <sup>-3</sup>	0.757	0.516	0.308	0.623	0.298	1.123

maps. Crystal data and refinement parameters are compiled in Table 2, and other technical data are available in the supplementary material.

**Refinement details and comments on structures:** **1** 123 K structure: O2 exhibited large anisotropic thermal parameters; **5**: no hydrogen atom was included in the refinement for the OH group; **6**: the structure contains a disordered ethanol molecule of solvation, no hydrogen atoms were included in the refinement for the solvent molecule, the residual electron density was located in the solvent region; **7**: oxygen atom O2 exhibited large and prolate thermal parameters; **8**: no hydrogen atoms were included in the refinement for the OH group of the solvate methanol molecules, the solvent molecule exhibited high displacement parameters indicating possible disorder. However, all attempts to model this gave less satisfactory refinements.

In several structures oxygen atom O2 (*e. g.*, the carbonyl type oxygen) exhibited high displacement parameters, significantly larger than for O1 or any of the carbon atoms of the

quinoid system. Disorder is unlikely as an explanation, as only this oxygen and none of the neighboring carbon atoms was affected. Only the *tert*-butyl derivative, where this oxygen atom is involved in a hydrogen bond, and the bisgalvinol did not show this unusual phenomenon. Some structures exhibited a number of close H···H intermolecular contacts between the galvinol -OH and the *tert*-butyl groups. As the -OH hydrogen atoms were located in difference maps, these H···H intermolecular contacts are the result of the close intermolecular packing.

CCDC 766271 – 766276 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via [www.ccdc.cam.ac.uk/data\\_request/cif](http://www.ccdc.cam.ac.uk/data_request/cif).

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