PERKIN 2

Intramolecular O–H $\cdots$ O hydrogen bonds assisted by resonance. Correlation between crystallographic data and ^{1}H NMR chemical shifts

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A number of crystal structures of molecules where the π-conjugated $\cdots$ O=C−C=C−OH $\cdots$ β-diketone enol group is found to form intramolecular O−H $\cdots$ O hydrogen bonds and for which ^{1}H NMR spectroscopic data were known are discussed. Five of these structures, determined by X-ray diffraction techniques, are reported and the other 42 were retrieved from the Cambridge Structural Database. It is shown that all the descriptors of hydrogen-bond strength [*d*(O $\cdots$ O) shortening, increased enolic ^{1}H NMR chemical shift, *δ*(OH), and increased π-delocalization of the hydrogen-bonded heteroconjugated fragment] are mutually and linearly intercorrelated according to the rules defined by RAHB (resonance-assisted hydrogen bonding). Such a model is found to be of general applicability to all intramolecular O−H $\cdots$ O bonds observed in a variety of molecules of different complexity embedding the simple β-diketone enol fragment and to be extensible to other hydrogen-bonded conjugated compounds such as $\cdots$ O=C−C=C−C=C−OH $\cdots$ *δ*-diketone enols and $\cdots$ O=C−C=N−OH $\cdots$ *α*-keto-oximes. The proton chemical shifts, *δ*(OH), measured in $CDCl_3$ solutions are found to depend strongly on the O $\cdots$ O contact distances going from 8.6–10.1 ppm for weak non-resonant [2.59 ⩽ *d*(O $\cdots$ O) ⩽ 2.64 Å] to 14.9–19.0 ppm for the strongest resonant hydrogen bonds [2.41 ⩽ *d*(O $\cdots$ O) ⩽ 2.55 Å]. Comparison with ^{1}H NMR data obtained in the solid-state shows a strictly similar dependence of *δ*(OH) on *d*(O $\cdots$ O), irrespective of the very different experimental conditions and in spite of the fact that solution and solid-state values concern intramolecular and intermolecular hydrogen bonds, respectively.

Introduction

β-Diketone enols are compounds which show abnormally short intramolecular O−H $\cdots$ O hydrogen bonds with a limiting *d*(O $\cdots$ O) distance of 2.40 Å. In order to understand the electronic and steric features involved in determining this unusual strength, several theoretical and experimental studies have been performed.[1–8] It has been shown that the O $\cdots$ O distance shortening is associated with an increase of the π-delocalization along the heterodienic O=C−C=C−OH chain as well as with a decrease of the IR *ν*(OH) stretching frequencies up to *ca.* 2560 cm^{-1}.[2,3,9] Such interrelated phenomena have been interpreted in terms of RAHB (resonance-assisted hydrogen bonding) which is essentially a mechanism of synergistic reinforcement of hydrogen bonding and π-delocalization.[2] It has been further shown that these strong hydrogen bonds are mostly covalent in nature owing to the optimal mixing of two chemically and energetically equivalent resonance forms **Ia** $\longleftrightarrow$ **Ib** occurring when substituents R^1 and R^3 have group electronegativities alike (*e.g.* two alkyl and/or aryl groups).[10,11] When, conversely, the two resonant forms are not equivalent a weakening of the hydrogen-bond strength can be expected which produces a lengthening of the *d*(O $\cdots$ O) distance, as observed in β-keto ester and β-keto amide enols wherein forms **IIa** and **II′a** are definitely more stable than **IIb** and **II′b**, respectively.[1,11]

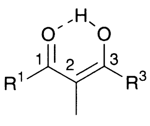
In principle, the RAHB model should be applicable to intramolecular O−H $\cdots$ O hydrogen bonds in other π-conjugated compounds even more complex than simple β-diketone enols. To verify this hypothesis, the structures of five new compounds containing the β-diketone enol fragment **I** coupled with other heteroconjugated systems (**1**–**3**) as well as the alternative motif **V** of the α-keto-oxime conjugated moiety (**4**, **5**) have been determined by X-ray crystallographic methods. Structural results are compared with ^{1}H NMR chemical shifts of the enolic proton, finding that the shortening of the O−H $\cdots$ O bond in the compounds investigated is coupled with an often remarkable downfield shift of the enolic (or oximinic) proton signal. Systematic comparison of present results with those of a number of other crystal structures containing a variety of resonant O−H $\cdots$ O intramolecular hydrogen bonds and for which NMR spectroscopic data were available makes it possible to show that all the descriptors of hydrogen-bond strength [*d*(O $\cdots$ O) shortening, increase of the enolic ^{1}H NMR *δ*(OH) chemical shift and increased delocalization of the intramolecularly hydrogen-bonded keto–enol heteroconjugated cycle] are mutually intercorrelated according to the rules defined by the RAHB model and that this occurs for all molecules reducible to schemes **I**–**V**, irrespective of their molecular complexity and of the number of other π-conjugated systems crossing the molecules themselves.

Experimental

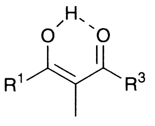
Structural characterization of compounds 1–5

Compounds **1**: 3-acetyl-4-hydroxy-6-methyl-2*H*-pyran-2-one and **2**: 3,5-bis(1-hydroxyethylidene)pyran-2,4,6-trione were purchased from Aldrich and recrystallized from ethanol. Compound **3**: 5-acetyl-4-hydroxy-3(1-phenylaminoethylidene)-3*H*-pyran-2,6-dione was synthesized according to reported procedures[12] and crystals suitable for X-ray diffraction were obtained by recrystallization from a mixture of methanol and $CHCl_3$. Compounds **4**: 5,5-dimethylcyclohexane-1,2,3-trione 2-oxime and **5**: 1,3-diethyl-2-thioxo-dihydropyrimidine-4,5,6-trione 5-oxime were synthesized using reported methods[13] by nitrosation of dimedone (5,5-dimethylcyclohexane-1,3-dione) and 1,3-diethyl-2-thiobarbituric acid, respectively; yellow and deep-yellow crystals for **4** and **5**, respectively, were obtained from ethyl acetate.

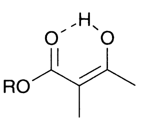
Crystal data, data collection and refinement details are given



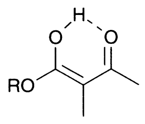
Ia



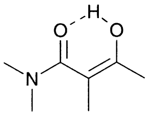
Ib



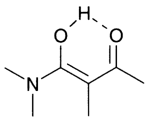
IIa



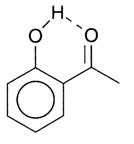
IIb



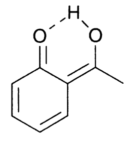
II'a



II'b



IIIa



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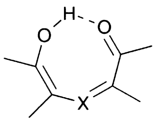
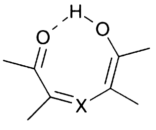
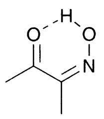


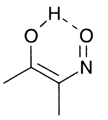
IVa



IVb



Va

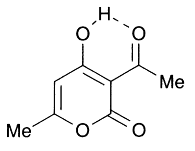


Vb

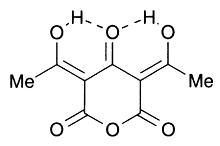
in Table 1. X-Ray intensities were collected at room temperature on an Enraf-Nonius CAD4 diffractometer using graphite monochromated Mo-Kα radiation ($\lambda = 0.710\,60$ Å) with the $\omega/2\theta$ scan technique. Lattice constants were determined by least-squares fitting of the setting angles of 25 reflections in the range $8 \leqslant \theta \leqslant 12°$. Intensities of three standard reflections were measured every 2 h and did not show significant variations for any of the five compounds investigated. All intensities were corrected for Lorentz and polarization effects. Scattering factors were taken from ref. 14. Structures were solved by direct methods using the SIR88 package[15] and all other calculations accomplished by using the MOLEN package[16] and PARST.[17]

The structures of compounds **1**, **3** and **4** were refined by full-matrix least squares with anisotropic non-H atoms and isotropic H atoms; the structure of compound **2** by full-matrix least squares (in two blocks for the final anisotropic cycles) with anisotropic non-H and isotropic H atoms; the structure of compound **5** by full-matrix least squares with anisotropic non-H atoms and isotropic hydrogens with the exception of hydrogen H(2) bonded to O(2) which, because of instability during the refinement, was given a fixed position determined from the ΔF synthesis. A selection of bond distances and angles is reported in Table 2, while hydrogen bond parameters are given in Table 3 and ORTEP[18] views of the five compounds in Fig. 1. ^{1}H NMR spectra were recorded in $CDCl_3$ solution on a Bruker FF WP-80 spectrometer.

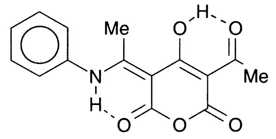
Atomic coordinates, bond lengths and angles, and thermal



1



2



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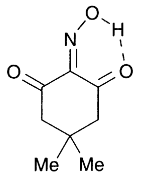
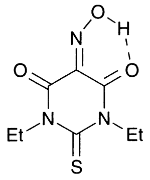


4



5

parameters have been deposited at the Cambridge Crystallographic Data Centre (CCDC). For details of the deposition scheme, see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 2*, 1997, Issue 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 188/61.

All crystal data of other structures discussed in the paper have been retrieved from the Cambridge Structural Database (version April 1996)[19] using the criterion: $R < 0.10$ and σ(C–C) < 0.010.

Description of structures 1–5

Compound **1** is found to adopt the 4-hydroxy tautomeric form and its asymmetric unit contains two independent molecules without significant differences in bond distances and angles. The short intramolecular $O-H\cdots O$ bond [$d(O\cdots O) = 2.472$ Å (on average)] is associated with a large value of the ^{1}H NMR chemical shift [$\delta(O-H) = 16.7$]. Comparison of actual and standard distances[20] indicates a remarkable delocalization of the heteroconjugated O(1)=C(1)–C(2)=C(3)–O(2)H β-diketone enol system as well as of the other π-conjugated atomic chains occurring in the molecule, *i.e.*: O(1)=C(1)–C(2)=C(3)–C(4)=C(5)–O(4) and HO(2)–C(3)=C(2)–C(6)=O(2).

Compound **2** exhibits double enolization giving rise to a symmetric molecule of crystallographic *mm* symmetry, which is most probably to be ascribed to crystal disorder as indicated by the orientations of its thermal ellipsoids (Fig. 1). The values of $\delta(OH) = 16.58$ and $d(O\cdots O) = 2.412$ Å are both indicative of a very strong intramolecular $O-H\cdots O$ bond. Both interconnected β-diketone enol groups display an extended π-delocalization not shared by the anhydride O=C–O–C=O fragment.

Compound **2** reacts dissymmetrically with aniline forming compound **3** where the single-Schiff base NH group forms a further resonant $N-H\cdots O$ bond with the oxygen of the anhydride moiety [$d(N\cdots O) = 2.575$ Å, $\delta(NH) = 13.66$ ppm]. The remaining O(2)=C(3)–C(2)=C(1)–O(1)H β-diketone enol moiety is similar to that found in **1**, though involved in a greater number of π-conjugated systems [*i.e.* HO(1)–C(1)=C(2)–C(5)=O(3), O(2)=C(3)–C(2)=C(1)–C(7)=C(8)–N(1)H and O(5)=C(6)–C(7)=C(8)–N(1)H] whose delocalization might be responsible for the exceptionally strong $O-H\cdots O$ bond formed [$d(O\cdots O) = 2.407$ Å] and of the remarkable downfield ^{1}H NMR chemical shift of 19.0 ppm.

Structures **4** and **5** are the first structural determinations of compounds containing the intramolecularly hydrogen-bonded α-keto–oxime system **V**. Though the observed hydrogen bonds [$d(O\cdots O) = 2.524$ and 2.522 Å in **4** and **5**, respectively] are

Table 1 Crystal data and summary of experimental details for compounds **1**–**5**

	1	**2**	**3**	**4**	**5**
Formula	$C_8H_8O_4$	$C_9H_8O_6$	$C_{15}H_{13}O_5N$	$C_8H_{11}O_3N$	$C_8H_{11}SO_3N_3$
M_r	168.15	212.16	287.27	169.18	229.26
Space group	$P2_1/a$	$Cmcm$	$C2/c$	$P2_1/c$	$P2_1/n$
Crystal system	Monoclinic	Orthorhombic	Monoclinic	Monoclinic	Monoclinic
a/Å	7.408(1)	6.373(2)	30.916(4)	7.921(1)	9.078(2)
b/Å	11.452(3)	7.126(1)	4.929(1)	5.952(3)	7.689(2)
c/Å	18.162(3)	19.214(2)	21.348(3)	17.801(3)	15.048(2)
α/°	90	90	90	90	90
β/°	91.43(2)	90	124.20(1)	96.37(1)	100.17(1)
γ/°	90	90	90	90	90
V/Å^3	1540.4(6)	872.6(4)	2690.6(9)	834.1(4)	1033.8(4)
Z	8	4	8	4	4
D_c g cm^{-3}	1.45	1.61	1.42	1.35	1.47
F(000)	704	440	1200	360	480
μ(Mo-Kα)/cm^{-1}-	1.101	1.301	1.007	0.969	2.907
Crystal size/mm^3	0.28 × 0.48 × 0.55	0.12 × 0.24 × 0.40	0.10 × 0.12 × 0.50	0.19 × 0.24 × 0.60	0.15 × 0.18 × 0.24
Independent reflections	4480	530	2927	1898	2246
Observed reflections N_o	1874 [$I > 2\sigma(I)$]	241 [$I > 2\sigma(I)$]	1138 [$I > 2\sigma(I)$]	1430 [$I > 3\sigma(I)$]	902 [$I > 2\sigma(I)$]
θ_{min}–θ_{max} (°)	2–30	2–27	2–27	2–28	2–27
hkl range	−10, 10; 0, 16; 0, 25	0, 8; 0, 9; 0, 24	−39, 39; 0, 6; 0, 27	0, 10; 0, 7; −23, 23	−11, 11; 0, 9; 0, 19
R [a]	0.058	0.063	0.061	0.041	0.080
Rw [b]	0.083	0.090	0.053	0.058	0.069
p [c]	0.06	0.04	0.02	0.04	0.03
No. of variables (N_v)	281	40	242	153	176
N_o/N_v	6.7	6.0	4.7	9.3	5.1
Max shift/error	0.02	0.03	0.02	0.01	0.04
GOF [d]	2.18	3.14	1.82	1.99	2.14
Largest ΔF peak/e Å^{-3}	0.24	0.13	0.12	0.20	0.43

[a] $R = \Sigma|\Delta F|/\Sigma|F_o|$. [b] $Rw = (\Sigma w|\Delta F|^2/\Sigma w|F_o|^2)^{\frac{1}{2}}$. [c] $w = 4F_o^2/[\sigma^2(I) + (pF_o^2)^2]$. [d] $\mathrm{GOF} = [\Sigma|\Delta F|^2/(N_o - N_v)]^{\frac{1}{2}}$.

Table 2 Selected bond distances (Å) for compounds **1**–**5**

1			
O(1A)–C(1A)	1.245(4)	O(1B)–C(1B)	1.241(4)
O(2A)–C(3A)	1.306(3)	O(2B)–C(3B)	1.305(4)
O(3A)–C(6A)	1.204(3)	O(3B)–C(6B)	1.207(3)
O(4A)–C(5A)	1.356(3)	O(4B)–C(5B)	1.363(3)
O(4A)–C(6A)	1.400(4)	O(4B)–C(6B)	1.393(4)
C(1A)–C(2A)	1.432(4)	C(1B)–C(2B)	1.452(4)
C(2A)–C(3A)	1.399(4)	C(2B)–C(3B)	1.404(4)
C(2A)–C(6A)	1.445(4)	C(2B)–C(6B)	1.437(4)
C(3A)–C(4A)	1.419(4)	C(3B)–C(4B)	1.406(4)
C(4A)–C(5A)	1.335(4)	C(4B)–C(5B)	1.333(4)
2			
O(1)–C(1)	1.294(8)	C(1)–C(2)	1.437(7)
O(2)–C(3)	1.332(8)	C(2)–C(3)	1.444(9)
O(3)–C(5)	1.180(8)	C(2)–C(5)	1.433(8)
O(4)–C(5)	1.405(7)		
3			
O(1)–C(1)	1.303(6)	C(1)–C(2)	1.424(4)
O(2)–C(3)	1.264(7)	C(1)–C(7)	1.425(5)
O(3)–C(5)	1.204(5)	C(2)–C(3)	1.429(6)
O(4)–C(5)	1.394(5)	C(2)–C(5)	1.421(7)
O(4)–C(6)	1.375(4)	C(6)–C(7)	1.434(7)
O(5)–C(6)	1.215(5)	C(7)–C(8)	1.423(4)
N(1)–C(8)	1.317(5)		
4			
O(1)–C(1)	1.207(2)	N(1)–C(2)	1.291(2)
O(2)–N(1)	1.357(2)	C(1)–C(2)	1.506(2)
O(3)–C(3)	1.230(2)	C(2)–C(3)	1.479(2)
5			
O(1)–C(1)	1.214(7)	N(1)–C(2)	1.285(9)
O(2)–N(1)	1.341(8)	C(1)–C(2)	1.435(8)
O(3)–C(3)	1.212(7)	C(2)–C(3)	1.455(9)

definitely shorter than in non-resonant compounds (2.63–2.64 Å; *vide infra*), the O=C–C=N–OH fragment appears to be weakly delocalized. This is in agreement with the fact that the equilibrium **Va** $\longleftrightarrow$ **Vb** is naturally shifted towards the oxime form because of its greater stability with respect to nitroso compounds.[21,22]

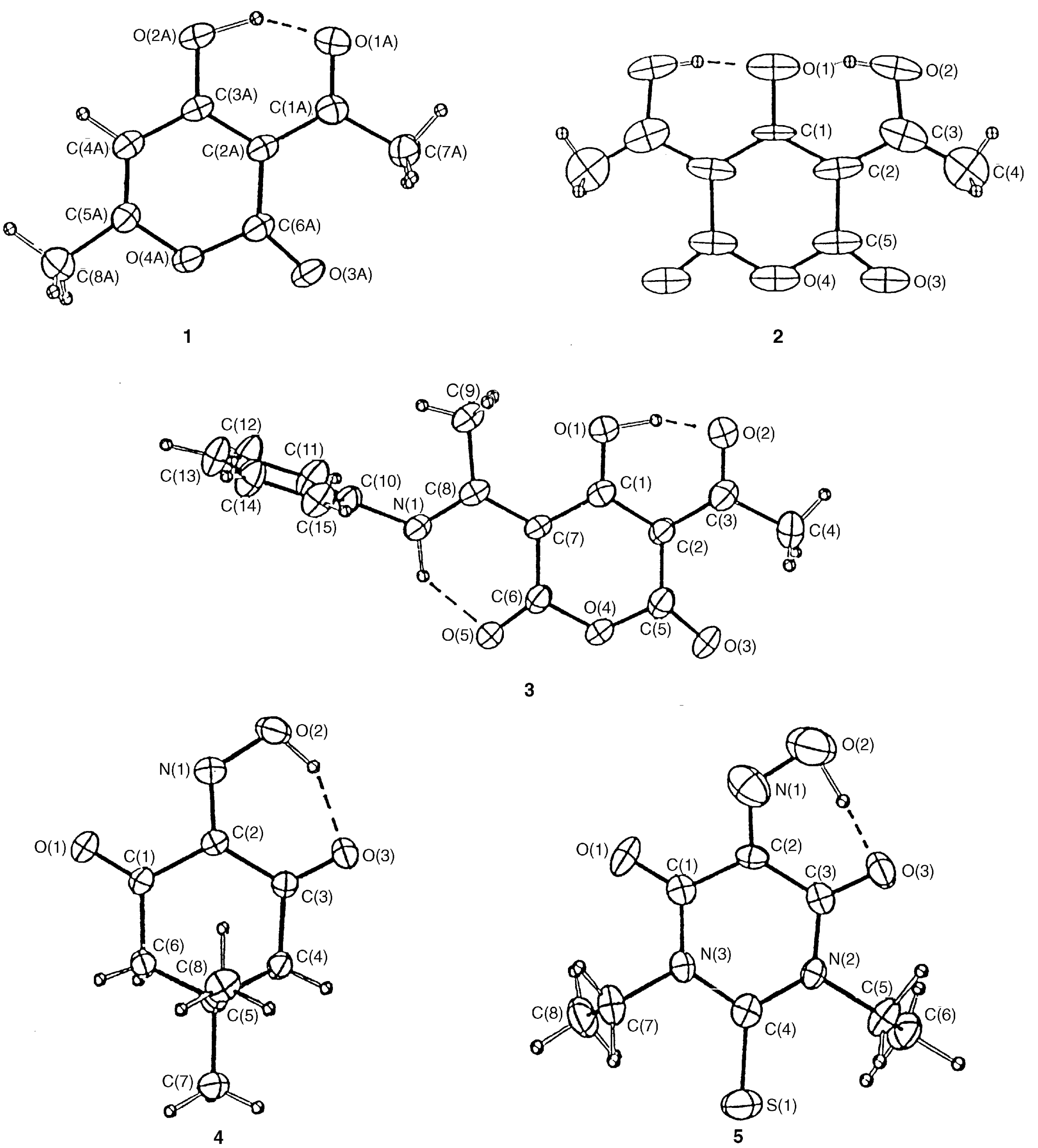
Table 3 Hydrogen bonding parameters (Å and degrees), for compounds **1**–**5**

Compound	A–H	A···B	A–H···B
1	O(2A)–H	O(2A)···O(1A)	O(2A)–H···O(1A)
	1.13(3)	2.469(3)	148(2)
	O(2B)–H	O(2B)···O(1B)	O(2B)–H···O(1B)
	1.08(3)	2.474(3)	154(2)
2	O(2)–H	O(2)···O(1)	O(2)–H···O(1)
	0.92(8)	2.412(7)	168(5)
3	O(1)–H	O(1)···O(2)	O(1)–H···O(2)
	1.07(4)	2.407(5)	158(4)
	N(1)–H	N(1)···O(5)	N(1)–H···O(5)
	0.95(5)	2.575(5)	138(4)
4	O(2)–H	O(2)···O(3)	O(2)–H···O(3)
	0.94(2)	2.524(2)	152(1)
5	O(2)–H	O(2)···O(3)	O(2)–H···O(3)
	1.14(8)	2.552(7)	165(6)

Discussion

All compounds investigated display short or very short intramolecular O–H···O bonds in the range $2.41 \leqslant d(\mathrm{O\cdots O}) \leqslant 2.55$ Å, significant increases of the π-delocalization of their hydrogen bonded conjugated systems, and remarkable deshieldings of the ^{1}H NMR δ(OH) enolic proton signal which is shifted from the usual range of some 3–7 ppm, in the absence of hydrogen bonding, to the present range of 16–19 ppm. This last effect is most probably due to the hydrogen-bond-induced lengthening of the O–H distance reportedly associated with strong hydrogen bonds[10,23,24] but difficult to appreciate by X-ray diffraction methods.

Generally speaking, all present experimental findings agree with the RAHB model[2,10] though this preliminary result cannot be accepted without a more critical comparison with other literature data. This is attempted in Table 4, which reports the relevant parameters [d(O···O), d(C=O), d(C–O), λ and δ(OH)] for a number of compounds (whose chemical formulae are sketched in **6**–**47**) containing at least one resonant ···O=C–C=C–OH··· intramolecular hydrogen-bonded ring



1 2 3 4 5

Fig. 1 ORTEP[18] views of the crystal structures of compounds **1–5**

(or a larger one as in **36** and **37**) and for which both crystal structure and ^{1}H NMR data were available. Three more compounds (**45–47**) having a similar hydrogen-bonded ring of non-resonant type have been added for the sake of comparison. The π-delocalization index, λ, has been evaluated as $\lambda = 1 - \langle 2 - n(\mathrm{C{=}O}),\ n(\mathrm{C{-}O}) - 1 \rangle$, that is as the complement to unity of the average between the decrease of the C=O and the increase of the C–O bond orders, *n*, defined by the Pauling formula[60] $d(n) - d(1) = -c \log_{10} n$, where $d(1)$ = single bond and $d(n)$ = *n*-ple bond distances and *c* is a constant to be determined. Parameters used in the Pauling formula were: C(sp^2)–O(sp^2), $d(1) = 1.38$, $d(2) = 1.20$ Å, $c = 0.598$; N(sp^2)–O(sp^2), $d(1) = 1.42$, $d(2) = 1.225$ Å, $c = 0.648$. For a generic mesomeric equilibrium **Ia** $\longleftrightarrow$ **Ib**, λ assumes the values of 1.0, 0.0 and 0.5 for **Ia**, **Ib** and the 1:1 mixture of **Ia** and **Ib**, respectively.

The intramolecular hydrogen bonds taken into account in Table 4 can be profitably divided according to the following classification.

Class A: β-diketone enols (**I**; compounds **1**, **3**, **6–27**).

Class B: β-ketoester (**II**; compounds **32–34**) or β-ketoamides (**II′**; compound **35**) enols.

Class C: 2-hydroxybenzoketones (**III**; compounds **38–45**).

Classes A′, C′: β,β′-triketone dienols forming hydrogen-bonded bicycles of type A + A (compounds **2** and **28**) or A + C (compounds **29–31**).

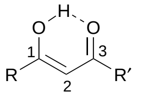
Class D: δ-diketone enols (**IV**; compounds **36** and **37**).

Class E: α-keto-oximes (**V**; compounds **4** and **5**).

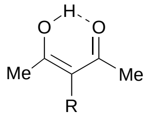
Class F: non-conjugated systems (compounds **45–47**).

Table 5 reports the $d(\mathrm{O\cdots O})$, λ and δ(OH) ranges for compounds of Table 4 arranged according to the chemical classes above. Data are summarized in Figs. 2 and 3 as λ *vs.* $d(\mathrm{O\cdots O})$ and δ(OH) *vs.* $d(\mathrm{O\cdots O})$ scatterplots wherein single points are marked by numbers which identify their relative classes.

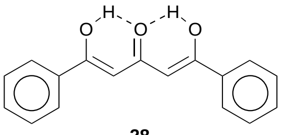
Compounds wherein the O–H⋯O bond is assisted by resonance (structures **I–V**; classes A–E) display systematically shorter O⋯O distances (2.41–2.60 Å) and higher downfield proton chemical shifts (19.0–11.8 ppm) than those where π-resonance is interrupted [class F: $d(\mathrm{O\cdots O}) = 2.59$–$2.64$ Å; δ(OH) = 10.1–8.6 ppm]. This is efficiently illustrated by compound **45** endowed with both a resonant [$d(\mathrm{O\cdots O}) = 2.472$ Å; λ = 0.71; δ(OH) = 16.0 ppm] and a non-resonant hydrogen bond



6 R = R′= Ph
7 R = Ph; R′= 4′-NO$_2$–Ph
8 R = Ph; R′= 4′-OMe–Ph
9 R = Ph; R′= Mesityl
10 R = 4′-NO$_2$–Ph; R′= Mesityl
11 R = Mesityl; R′= 3′-NO$_2$–Ph
12 R = Mesityl; R′= 2′-NO$_2$–Ph
13 R = NO$_2$–Ph; R′= 4′-OMe–Ph
14 R = Mesityl; R′= 4′-OMe–Ph
15 R = Ph; R′= 4′-Cl–Ph
16 R = Ph; R′= Me
17 R = CF$_3$; R′= Thienyl
18 R = 2′,4′-di-OMe–Ph; R′= 1′,3′-Benzodioxol-5′-yl
19 R = Ph; R′= 1′-Hydroxypropen-2′-on-1′-yl



20 R = 4′-Biphenyl
21 R = 4′-OMe–Ph
22 R = 4′-NO$_2$–Ph
23 R = 4′-O–Ph–Ph
24 R = 4′-Pr^i–Ph
25 R = 2′-4′-di-OMe–Ph
26 R = H
27 R = 1′,3′-di-Me-1′-hydroxypropen-3′-on-2′-yl



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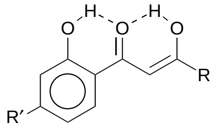
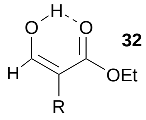


29 R = Ph; R′= H
30 R = 4′-OMe–Ph; R′= H
31 R = Ph; R′=OMe



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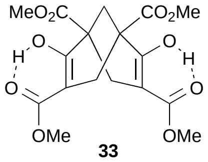

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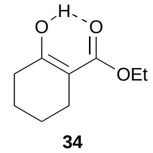

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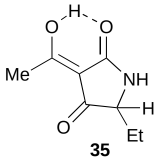

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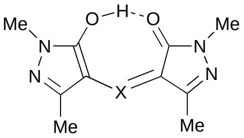
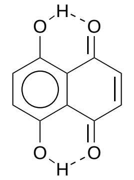


36 X = CH
37 X = N



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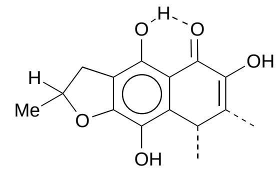
[d(O···O) = 2.587 Å; λ = 0.94; δ = 10.1 ppm] at the same time. Broadly speaking the increasing π-delocalization of the O=C–C=C–OH fragment (*i.e.* the decreasing λ) appears to be linearly related to the decrease in the O···O contact distance (Fig. 2; correlation coefficient r = 0.80) and the progressive raising of the downfield chemical shift (scatterplot not shown: r = −0.82) and similar delocalization effects are produced by the longer O=C–C=C–C=C–OH conjugated fragment present in δ-diketone enols (**IV**; compounds **36** and **37** of class D). The λ *versus* d(O···O) plot presented here (Fig. 2) is rather more scattered than other similar plots previously given for more restricted chemical classes[2,3,9–11] and this can be ascribed to the greater variety of compounds considered where the basic β-diketone enol hydrogen-bonded ring (**I**) is perturbed by heteroatoms (**V**), fused aromatic rings (**III**) and further π-conjugated systems heaped up with it.

The strongest hydrogen bonds appear to be mostly associated with more symmetrical arrangements on the two sides of the hydrogen bond (1,3-substituents in **I**).[10,11] Such a symmetry is perfectly achieved in the β-diketones of class A having R^1 = R^3 and in the two δ-diketone enols of class D, which are in fact endowed with very short O···O distances [2.42 ⩽ d(O···O) ⩽ 2.49 Å], higher downfield shifts [17.8 ⩾ δ(OH) ⩾ 16.9 ppm] and almost complete delocalization (0.50 ⩽ λ ⩽ 0.61). The strength of the hydrogen bond is not significantly reduced as a result of 1,3-disubstitution by different aryl or alkyl substituents [class A (R^1 ≠ R^3) of Table 5: 2.41 ⩽ d(O···O) ⩽ 2.55; 19.0 ⩾ δ(OH) ⩾ 14.9 ppm; 0.52 ⩽ λ ⩽ 0.71]. The two longest distances in this class are observed, in agreement with expectation, with compounds **17**



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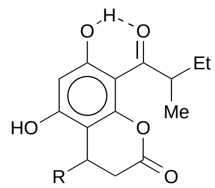

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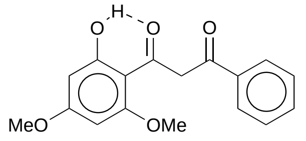

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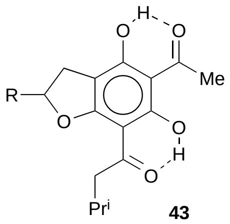

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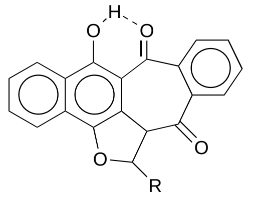

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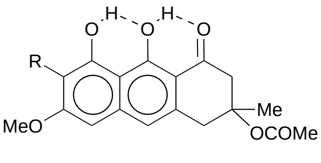

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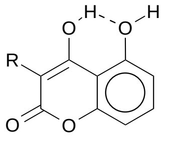

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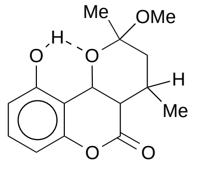

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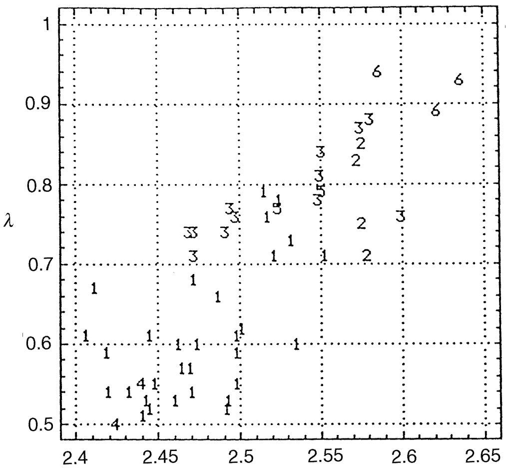

Fig. 2 Scatter plot of the delocalization parameter λ *versus* hydrogen-bond contact distance d(O···O) for compounds **1**–**47** of Table 4. Symbols: **1** = classes A and A′; **2** = class B; **3** = classes C and C′; **4** = class D; **5** = class E and **6** = class F (see Table 5).

Table 4 Geometrical parameters [d(O···O), d(C=O), d(C–O) distances, Å]; π-conjugation indicators λ, and ^{1}H NMR δ(OH) chemical shifts for the intramolecular O–H···O hydrogen bonds of compounds **1**–**47**. Classes A, A′, B, C, C′, D, E and F are defined in the text

Comp.	Class	d(O···O)/Å	d(C=O)/Å	d(C–O)/Å	λ	Ref.	δ(OH)	Ref.
1	A	⟨2.472⟩	⟨1.243⟩	⟨1.306⟩	⟨0.68⟩	p.w.	16.7	25
2	A′	2.412	1.291	1.332	0.67	p.w.	16.6	25
3	A	2.407	1.264	1.303	0.61	p.w.	19.0	25
4	E	2.524	1.230	1.357[a]	0.77	p.w.	16.0	p.w.
5	E	2.552	1.212	1.341[a]	0.79	p.w.	16.2	p.w.
6	A	2.463	1.273	1.311	0.60	26	16.9	9
7	A	2.465	1.288	1.313	0.57	9	16.7	9
8	A	2.470	1.278	1.304	0.57	9	16.5	9
9	A	2.461	1.281	1.294	0.53	9	16.4	9
10	A	2.502	1.265	1.309	0.62	9	16.2	9
11	A	2.492	1.278	1.287	0.52	9	16.2	9
12	A	2.554	1.247	1.321	0.71	9	15.3	9
13	A	⟨2.433⟩	⟨1.284⟩	⟨1.297⟩	0.54	9	16.9	9
14	A	2.499	1.269	1.300	0.59	9	16.5	9
15	A	2.471	1.283	1.299	0.54	27	16.8	27
16	A	2.498	1.276	1.294	0.55	28	16.1	29
17	A	⟨2.536⟩	⟨1.270⟩	⟨1.308⟩	0.60	30	14.9	31
18	A	2.499	1.281	1.322	0.61	32	17.2	32
19	A	2.487	1.264	1.323	0.66	33	15.7	34
20	A	2.441	1.290	1.292	0.51	35	16.7	35
21	A	2.449	1.283	1.301	0.55	36	16.6	36
22	A	2.445	1.270	1.309	0.61	37	16.8	37
23	A	2.443	1.284	1.292	0.53	37	16.7	37
24	A	2.419	1.281	1.315	0.59	37	16.8	37
25	A	2.445	1.289	1.296	0.52	38	16.6	38
	A	2.475	1.271	1.306	0.60	38	16.6	38
26	A	2.493	1.280	1.289	0.53	39	15.4	39
27	A	2.420	1.295	1.310	0.54	40	16.8	37
28	A′	2.518	1.288	1.337	0.76	41	14.8	42
	A′	2.526	1.288	1.341	0.78	41	14.8	42
29	A′	⟨2.533⟩	⟨1.265⟩	⟨1.322⟩	0.73	32	15.5	32
	C′	⟨2.582⟩	⟨1.265⟩	⟨1.350⟩	0.88	32	12.1	32
30	A′	⟨2.522⟩	⟨1.270⟩	⟨1.321⟩	0.71	43	15.8	43
	C′	⟨2.575⟩	⟨1.270⟩	⟨1.353⟩	0.87	43	12.2	43
31	A′	2.516	1.272	1.343	0.79	44	15.4	44
	C′	2.552	1.272	1.351	0.84	44	12.5	44
32	B	2.557	1.250	1.340	0.75	45	11.8	45
33	B	2.573	1.226	1.346	0.83	46	13.0	46
34	B	2.576	1.217	1.339	0.85	47	12.1	48
35	B	2.580	1.256	1.340	0.71	49	11.8	49
36	D	2.425	1.276	1.277	0.50	50	17.8	51
37	D	⟨2.440⟩	⟨1.265⟩	⟨1.281⟩	0.55	50	17.3	50
38	C	⟨2.600⟩	⟨1.246⟩	⟨1.343⟩	0.76	51	12.4	51
39	C	⟨2.550⟩	⟨1.244⟩	⟨1.360⟩	0.81	54	12.4	54
40	C	⟨2.549⟩	⟨1.256⟩	⟨1.362⟩	0.78	54	12.6	54
41	C	2.494	1.233	1.327	0.77	55	13.6	55
42	C	2.497	1.249	1.348	0.76	44	13.7	44
43	C	2.473	1.245	1.332	0.74	56	15.8	56
	C	2.491	1.250	1.338	0.74	56	14.7	56
44	C	2.469	1.253	1.343	0.74	57	15.4	57
45	C	2.472	1.261	1.341	0.71	58	16.0	58
	F	2.587		1.364	0.94[b]	58	10.1	58
46	F	2.637		1.364	0.93[b]	59	10.1	59
47	F	2.628		1.353	0.89[b]	59	8.6	59

p.w. present work. ⟨ ⟩ Averaged value. [a] N–O distances. [b] λ values calculated from C–O bond length only.

[d(O···O) = 2.536 Å; λ = 0.60; δ(OH) = 14.9 ppm] carrying the two more dissimilar substituents (CF_3 and thienyl)[30,31] and **12** [d(O···O) = 2.554 Å; λ = 0.71; δ(OH) = 15.3 ppm] where the dissymmetry is produced by a donor–acceptor interaction between an oxygen of the *o*-NO_2 group and the carbonyl carbon.[9]

Molecular dissymmetries which are clearly able to weaken the intramolecular hydrogen bonds are of three different sorts. The first is typical of β-keto ester (**II**; class B) or β-keto amide (**II′**; class B) enols for which it has been previously shown[11] that both d(O···O) and λ are changed from the values normally found in β-diketone enols [d(O···O) = 2.46 ± 0.04 Å, λ = 0.60 ± 0.07] to d(O···O) = 2.57 ± 0.03 and λ = 0.82 ± 0.04. Similar results are found here for distances [2.56 ⩽ d(O···O)/Å ⩽ 2.58] and π-delocalizations (0.71 ⩽ λ ⩽ 0.85) and the effect of the hydrogen bond weakening is confirmed by the lowering of the chemical shift (13.0 ⩾ δ(OH) ⩾ 11.8) with respect to the range observed in β-diketones of class A [19.0 ⩾ δ(OH) ⩾ 14.9; Table 5].

A similar though slightly smaller weakening of the O–H···O bond [2.47 ⩽ d(O···O)/Å ⩽ 2.60; 0.71 ⩽ λ ⩽ 0.81; 16.0 ⩾ δ(OH) ⩾ 12.4] is produced by dissymmetrical fusion of the hydrogen-bonded enolone with a single aromatic ring (**III**; class C). This can be more simply explained in terms of hindered **IIIa** $\longleftrightarrow$ **IIIb** resonance because form **IIIa** is made more stable than form **IIIb** by its aromatic stabilization energy. Analogous considerations can be applied to the α-keto-oximes (**V**; class E); oximes are well known to be much more stable than nitroso compounds which, in fact, spontaneously transform into the former.[21,22,61,62] This makes form **Va** energetically more favoured with respect to **Vb** hindering complete π-delocalization within the heterodiene and making rather weak

Table 5 Ranges of $d(\mathrm{O}\cdots\mathrm{O})$ distances (Å), π-delocalization parameter λ and NMR ^{1}H chemical shifts $\delta(\mathrm{OH})$

Class	$d(\mathrm{O}\cdots\mathrm{O})$/Å	λ	$\delta(\mathrm{OH})$
A, D (**I**: $R^1 = R^3$; **IV**)	2.42–2.49	0.50–0.61	17.8–16.9
A (**I**: $R^1 \neq R^3$)	2.41–2.55	0.52–0.71	19.0–14.9
A′	2.52–2.53	0.71–0.79	15.8–14.8
B (**II** and **II**′)	2.56–2.58	0.71–0.85	13.0–11.8
C (**III**)	2.47–2.60	0.71–0.81	16.0–12.4
C′	2.55–2.58	0.84–0.88	12.5–12.1
E (**V**)	2.52–2.55	0.77–0.79	16.2–16.0
F (non-resonant)	2.59–2.64	0.89–0.94	10.1–8.6

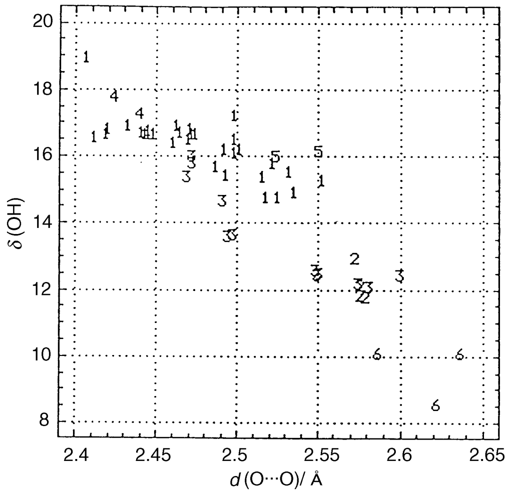

Fig. 3 Scatter plot of the ^{1}H NMR proton chemical shift $\delta(\mathrm{OH})$ *versus* hydrogen-bond contact distance $d(\mathrm{O}\cdots\mathrm{O})$ for compounds **1**–**47** of Table 4. Symbols: **1** = classes A and A′; **2** = class B; **3** = classes C and C′; **4** = class D; **5** = class E and **6** = class F (see Table 5).

the hydrogen bond formed [$2.52 \leqslant d(\mathrm{O}\cdots\mathrm{O})/\text{Å} \leqslant 2.55$; $0.77 \leqslant \lambda \leqslant 0.79$; $16.2 \geqslant \delta(\mathrm{OH}) \geqslant 16.0$].

Finally, accumulation of two resonant cycles on the same oxygen tends to weaken each separate hydrogen bond. This is apparent in compounds of class A′, which display systematically weaker bonds [$d(\mathrm{O}\cdots\mathrm{O}) = 2.52$–$2.53$ Å; $\lambda = 0.71$–0.79; $\delta(\mathrm{OH}) = 14.8$–$15.8$ ppm] than those of class A; in the same way, those belonging to class C′ give weaker hydrogen bonds [$d(\mathrm{O}\cdots\mathrm{O}) = 2.55$–$2.58$ Å; $\lambda = 0.84$–0.88; $\delta(\mathrm{OH}) = 12.1$–$12.5$ ppm] than those of class C. The only exception is represented by compound **2** which, in spite of being a β–β′-triketone dienol, exhibits an abnormally strong O–H···O interaction [$d(\mathrm{O}\cdots\mathrm{O}) = 2.41$ Å; $\lambda = 0.67$; $\delta(\mathrm{OH}) = 16.6$] which could be due to its perfect *mm* symmetry and then to the mixing of more than two resonant forms.[42] Unfortunately, the crystal structure is disordered so that bond distances are not so reliable.

Proton chemical shift data deserve further analysis. The $\delta(\mathrm{OH})$ *vs.* $d(\mathrm{O}\cdots\mathrm{O})$ plot (Fig. 3) is nearly linear with correlation coefficient $r = -0.88$. It cannot be compared with previous solution data which are essentially lacking, but only with those measured by solid state NMR spectroscopy.[63,64] In particular, Berglund and Vaugham[63] have reported a detailed account on proton chemical shift tensor (σ_{ij}) measurements on O–H···O bonded protons in solids and found that the shieldings parallel ($\sigma_{\parallel} = \sigma_{33}$) and perpendicular [$\sigma_{\perp} = (\sigma_{11} + \sigma_{22})/2$] to the O–H bond direction behave in a different way with respect to the variations of O···O distance. The former is practically independent of $d(\mathrm{O}\cdots\mathrm{O})$, while the latter depends on it in an essentially linear fashion. This, in turn, produces the linear relationship between the $d(\mathrm{O}\cdots\mathrm{O})$ and the average isotropic shift, defined as one third of the tensor trace value [$\sigma = (\sigma_{11} + \sigma_{22} + \sigma_{33})/3$]. It can be easily calculated that such average isotropic shift, expressed as σ_{TMS} (ppm) $= -\delta(\mathrm{OH})$ (ppm) (TMS = tetramethylsilane) is related to the contact $d(\mathrm{O}\cdots\mathrm{O})$ distance by the regression eqn. (1). The corresponding

$$-\sigma_{\mathrm{TMS}} = \delta(\mathrm{OH}) = -30.9\,(\pm 2.5)\, d(\mathrm{O}\cdots\mathrm{O}) + 94.7\,(\pm 6.5) \quad (1)$$
$$(n = 31,\ r = -0.92,\ F = 156.4)$$

regression expression for the solution data of Table 4 and Fig. 3 is eqn. (2), showing that the two sets of data are in

$$\delta(\mathrm{OH}) = -34.1\,(\pm 2.6)\, d(\mathrm{O}\cdots\mathrm{O}) + 100.3\,(\pm 6.4) \quad (2)$$
$$(n = 54,\ r = -0.88,\ F = 176.8)$$

remarkable agreement, particularly if due account is made of the substantially different experimental conditions wherein NMR spectra were recorded (single or powdered crystals on the one hand and mostly $CDCl_3$ solutions on the other) and in spite of the fact that solution values concern intramolecular hydrogen bonds while solid state data deal, with only one exception, with intermolecular ones.[65]

The linear dependence of σ and $\sigma_{\perp}$ on $d(\mathrm{O}\cdots\mathrm{O})$ has been interpreted in terms of theoretical quantum mechanical calculations[66] and parallels that already observed between $d(\mathrm{O}\cdots\mathrm{O})$ and the deuterium quadrupole coupling constant e^2qQ/h[63,67,68] while it is at variance with the IR stretching frequencies $\nu(\mathrm{OH})$ *versus* $d(\mathrm{O}\cdots\mathrm{O})$ plot[69,70] which displays a definite curvature and can be linearized only by plotting $\nu(\mathrm{OH})$ as a function of $n(\mathrm{O{-}H})$ (the bond order of the O–H bond) or of the O–H distance.[70]

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References

1 J. Emsley, *Struct. Bonding* (*Berlin*), 1984, **57**, 147.
2 G. Gilli, F. Bellucci, V. Ferretti and V. Bertolasi, *J. Am. Chem. Soc.*, 1989, **111**, 1023.
3 G. Gilli and V. Bertolasi, in *The Chemistry of Enols*, ed. Z. Rappoport, Wiley, New York, 1980, ch. 13, p. 713.
4 R. C. Haddon, *J. Am. Chem. Soc.*, 1980, **102**, 1807.
5 M. C. Etter, R. C. Hoye and G. M. Vojta, *Cryst. Rev.*, 1988, **1**, 281.
6 A. J. Vila, C. M. Lagier and A. C. Olivieri, *J. Phys. Chem.*, 1991, **95**, 5069.
7 M. J. T. Robinson, K. M. Rosen and J. D. B. Workman, *Tetrahedron*, 1977, **33**, 1655.
8 M. J. Frisch, A. C. Scheiner, H. F. Schaefer III and J. S. Binkley, *J. Chem. Phys.*, 1985, **82**, 4194.
9 V. Bertolasi, P. Gilli, V. Ferretti and G. Gilli, *J. Am. Chem. Soc.*, 1991, **113**, 4917.
10 P. Gilli, V. Bertolasi, V. Ferretti and G. Gilli, *J. Am. Chem. Soc.*, 1994, **116**, 909.
11 P. Gilli, V. Ferretti, V. Bertolasi and G. Gilli, in *Advances in Molecular Structure Research*, eds. M. Hargittai and I. Hargittai, JAI Press, Greenwich, CT, 1996, vol. 2, p. 67.
12 A. K. Kiang, S. F. Tan and S. Wong, *J. Chem. Soc. C*, 1971, 2721.
13 D. Von Günther, H. Günther and T. Günther, *J. Prakt. Chem.*, 1969, **311**, 162.
14 *International Tables for X-Ray Crystallography*, Kynoch Press, Birmingham, 1974, vol. 4, p. 71.
15 M. C. Burla, M. Camalli, G. Cascarano, C. Giacovazzo, G. Polidori, R. Spagna and D. Viterbo, SIR88, A Direct Methods Program for the Automatic Solution of Crystal Structures, *J. Appl. Crystallogr.*, 1989, **22**, 389.
16 MOLEN, An Interactive Structure Solution Procedure, Enraf-Nonius, Delft, The Netherlands, 1990.
17 M. Nardelli, *Comput. Chem.*, 1983, **7**, 95.
18 C. J. Johnson, ORTEP II, Report ORNL-5138, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1976.
19 F. H. Allen, S. Bellard, M. D. Brice, B. A. Cartwright, A. Doubleday, H. Higgs, T. Hummelink, B. G. Hummelink-Peters,

O. Kennard, W. D. S. Motherwell, J. R. Rogers and D. G. Watson, *Acta Crystallogr., Sect. B*, 1979, **35**, 2331.

20 F. H. Allen, O. Kennard, D. G. Brammer, L. Brammer, G. Orpen and R. Taylor, *J. Chem. Soc., Perkin Trans. 2*, 1987, S1.

21 V. Bertolasi, G. Gilli and A. C. Veronese, *Acta Crystallogr., Sect. B*, 1982, **38**, 502.

22 G. Gilli, V. Bertolasi and A. C. Veronese, *Acta Crystallogr., Sect. B*, 1983, **39**, 450.

23 T. Steiner and W. Saenger, *Acta Crystallogr., Sect. B*, 1994, **50**, 348.

24 I. Olovsson and P.-G. Jönsson, in *The Hydrogen Bond—Recent Developments in Theory and Experiments*, eds. P. Schuster, G. Zundel and G. Sandorfy, North-Holland, Amsterdam, 1976, vol. 2, ch. 8, p. 393.

25 S. F. Tan, K. P. Ang, H. L. Jayachandran, A. J. Jones and W. R. Begg, *J. Chem. Soc., Perkin Trans. 2*, 1982, 513.

26 R. D. G. Jones, *Acta Crystallogr., Sect. B*, 1976, **32**, 1807.

27 P. Gilli, V. Ferretti, V. Bertolasi and G. Gilli, *Acta Crystallogr., Sect. C*, 1992, **48**, 1798.

28 D. Semmingsen, *Acta Chem. Scand.*, 1972, **26**, 143.

29 M. Bassetti, G. Cerichelli and B. Floris, *Gazz. Chim. Ital.*, 1986, **116**, 579.

30 R. D. G. Jones, *Acta Crystallogr., Sect. B*, 1976, **32**, 1224.

31 L. R. Lintvedt and H. F. Holtzclaw, Jr., *J. Am. Chem. Soc.*, 1966, **88**, 2713.

32 S. W. Ng, A. H. Othman and S. N. A. Malek, *J. Chem. Crystallogr.*, 1994, **24**, 331.

33 B. Kaitner, G. Jovanovski and I. Janev, *Acta Crystallogr., Sect. C*, 1992, **48**, 127.

34 M. Poje and K. Balenovic, *J. Heterocycl. Chem.*, 1979, **16**, 417.

35 J. Emsley, L. Y. Y. Ma, P. A. Bates and M. B. Hursthouse, *J. Mol. Struct.*, 1988, **178**, 297.

36 J. Emsley, N. J. Freeman, P. A. Bates and M. B. Hursthouse, *J. Chem. Soc., Perkin Trans. 1*, 1988, 297.

37 J. Emsley, L. Y. Y. Ma, P. A. Bates, M. Motevalli and M. B. Hursthouse, *J. Chem. Soc., Perkin Trans. 2*, 1989, 527.

38 J. Emsley, L. Y. Y. Ma, S. A. Karlaulov, M. Motevalli and M. B. Hursthouse, *J. Mol. Struct.*, 1990, **216**, 143.

39 O. Gallardo, I. Csöregh and E. Weber, *J. Chem. Crystallogr.*, 1995, **25**, 769.

40 D. H. Dewar, J. E. Fergusson, P. R. Hentschel, C. J. Wilkins and P. P. Williams, *J. Chem. Soc.*, 1964, 688.

41 R. Cea-Olivares, I. Rodriguez, M. J. Rosales and R. A. Toscano, *Aust. J. Chem.*, 1987, **40**, 1127.

42 P. E. Hansen, S. Bolvig and T. Kappe, *J. Chem. Soc., Perkin Trans. 2*, 1995, 1901.

43 P. J. Cox, S. M. MacManus, S. K. Sharp, D. Adam and K. W. Muir, *J. Cryst. Spectr. Res.*, 1993, **23**, 431.

44 B. D. M. Cunningham, P. R. Lowe and M. D. Threadgill, *J. Chem. Soc., Perkin Trans. 2*, 1989, 1275.

45 B. Saha, S. C. Roy, G. O. S. V. Satyanarayana, U. R. Ghatak, A. Seal, S. Ray, R. Bandyopadhyay, M. Ghosh, B. Das and B. S. Basak, *J. Chem. Soc., Perkin Trans. 1*, 1985, 505.

46 M. D. Radcliffe, A. Gutierrez, J. F. Blount and K. Mislow, *J. Am. Chem. Soc.*, 1984, **106**, 682.

47 S. Forsen, F. Merenyi and M. Nilsson, *Acta Chem. Scand.*, 1964, **18**, 1208.

48 S. Rhodas, *J. Org. Chem.*, 1966, **31**, 171.

49 M. J. Nolte, P. S. Steyn and P. L. Wessels, *J. Chem. Soc., Perkin Trans. 1*, 1980, 1057.

50 U. Druck and W. Littke, *Acta Crystallogr., Sect. B*, 1980, **36**, 3002.

51 A. C. Olivieri, D. Sanz, R. M. Claramunt and J. Elguero, *J. Chem. Soc., Perkin Trans. 2*, 1993, 1597.

52 F. H. Herbstein, M. Kapon, G. M. Reisner, M. S. Lehman, R. B. Kress, R. B. Wilson, W. I. Shiau, E. N. Duesler, I. C. Paul and D. Y. Curtin, *Proc. R. Soc. London, Ser. A*, 1985, **399**, 295.

53 J. R. de la Vega, J. H. Busch, J. H. Schauble, K. L. Kunze and B. E. Haggert, *J. Am. Chem. Soc.*, 1982, **104**, 3295.

54 M. C. Carreiras, B. Rodriguez, M. C. de la Torre, A. Perales, M. R. Torres, G. Savona and F. Piozzi, *Tetrahedron*, 1990, **46**, 847.

55 C. H. Schwalbe and P. G. Waterman, *Acta Crystallogr., Sect. C*, 1983, **39**, 499.

56 J. A. Chan, E. A. Shultis, S. A. Carr, C. W. DeBrosse, D. S. Eggleston, T. A. Francis, L. J. Hyland, W. P. Johnson, L. D. Killmer, D. B. Staiger and J. W. Westley, *J. Org. Chem.*, 1989, **54**, 2089.

57 B. S. Joshi, D. H. Gawad, S. W. Pelletier, G. Kartha and K. Bhandary, *Tetrahedron Lett.*, 1984, **25**, 5847.

58 F. Delle Monache, F. Ferrari, G. B. Marini Bettolo, P. Maxfield, S. Cerrini, W. Fedeli, E. Gavuzzo and A. Vaciago, *Gazz. Chim. Ital.*, 1979, **109**, 301.

59 B. Castleberry, E. J. Valente and D. S. Eggleston, *J. Cryst. Spectr. Res.*, 1990, **20**, 583.

60 L. Pauling, *J. Am. Chem. Soc.*, 1947, **69**, 542.

61 I. L. Finar, *Organic Chemistry*, VI edn., Longman, Harlow, Essex, 1985, vol. 1, p. 366.

62 V. Ferretti, P. Gilli, V. Bertolasi and G. Gilli, *Cryst. Rev.*, 1996, **5**, 3.

63 B. Berglung and R. W. Vaugham, *J. Chem. Phys.*, 1980, **73**, 2037.

64 C. A. Jeffrey and Y. Yeon, *Acta Crystallogr., Sect. B*, 1986, **42**, 410.

65 C. A. Fyfe, *Solid State NMR for Chemists*, CFC Press, Guelph, 1983, p. 453.

66 C. McMichael Rohlfing, L. C. Allen and R. Ditchfield, *J. Chem. Phys.*, 1983, **79**, 4958.

67 B. Berglund, J. Lindgren and J. Tegenfeldt, *J. Mol. Struct.*, 1978, **43**, 179.

68 G. Soda and T. Chiba, *J. Chem. Phys.*, 1969, **50**, 439.

69 A. Novak, *Struct. Bonding (Berlin)*, 1974, **18**, 177.

70 V. Bertolasi, P. Gilli, V. Ferretti and G. Gilli, *Chem. Eur. J.*, 1996, **2**, 113.

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