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Conformations of substituted benzophenones

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The inclination of the two aryl rings (ring twists) in a series of benzophenone molecules has been examined. For each structure the dihedral angle (between the planes of the two sets of six aromatic C atoms) relates to both the steric considerations of the single molecule and the packing forces related to the crystal structure. Six new benzophenone structures are incorporated into the study including 2,2′-dihydroxy-4,4′-dimethoxybenzophenone (I), $C_{15}H_{14}O_5$, that appears to have the smallest reported twist angle, 37.85 (5)°, of any substituted benzophenone reported to date. Three further benzophenones, 4,4′-bis(diethylamino)benzophenone (II), $C_{21}H_{28}N_2O$, 3,4-dihydroxybenzophenone (III), $C_{13}H_{10}O_3$, and 3-hydroxybenzophenone (IV), $C_{13}H_{10}O_2$, have similar ring twists [49.83 (5), 49.84 (5) and 51.61 (5)°, respectively] that are comparable with the value of 54° found for the orthorhombic form of unsubstituted benzophenone. 4-Chloro-4′-hydroxybenzophenone (V), $C_{13}H_9ClO_2$, has a ring twist of 64.66 (8)° that is close to the value of 65° found in the metastable monoclinic form of unsubstituted benzophenone and 2-amino-2′,5-dichlorobenzophenone (VI), $C_{13}H_9Cl_2NO_2$, has a large ring twist of 83.72 (6)°. Comparisons with a further 98 substituted benzophenone molecules from the Cambridge Structural Database (CSD) have been made.

1. Introduction

Several benzophenones are used in industry, cosmetics, medicine and agriculture owing to their ability to absorb and scatter UV radiation in a harmless manner, thus protecting products and human skin from the damaging effects of UV radiation. For cosmetic and medicinal purposes, benzophenones effectively absorb light throughout the UVB range (λ = 290–320 nm) and also absorb some UVA light (λ = 320 to ~ 360 nm), as well as some UVC light ($\lambda \simeq$ 250–290 nm; Sweetman, 2007). These compounds, often combined with a sunscreen from a different class of compound, may therefore

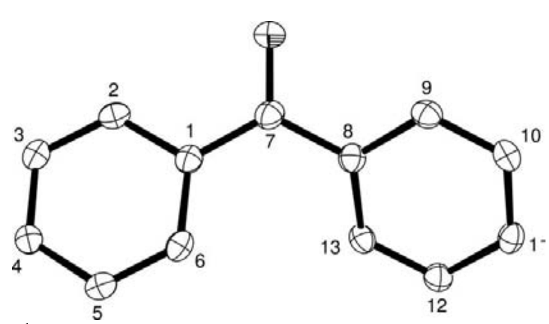


Figure 1
Benzophenone numbering scheme used in this study.

Table 1
Crystal data and structure analysis..

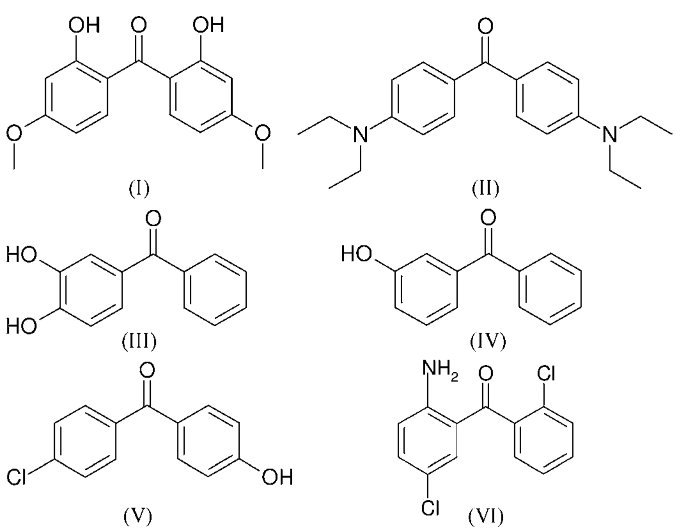
	(I)	(II)	(III)	(IV)	(V)	(VI)
Crystal data						
Chemical formula	$C_{15}H_{14}O_5$	$C_{21}H_{28}N_2O$	$C_{13}H_{10}O_3$	$C_{13}H_{10}O_2$	$C_{13}H_9ClO_2$	$C_{13}H_9Cl_2NO$
M_r	274.26	324.45	214.21	198.21	232.65	266.11
Cell setting, space group	Monoclinic, $P2_1/n$	Monoclinic, $P2_1/c$	Monoclinic, $C2/c$	Monoclinic, $P2_1/n$	Orthorhombic, $Pca2_1$	Monoclinic, $P2_1/c$
Temperature (K)	120 (2)	120 (2)	120 (2)	120 (2)	120 (2)	120 (2)
a, b, c (Å)	3.8466 (1), 25.1521 (12), 12.9802 (6)	16.8519 (6), 8.0488 (3), 14.3060 (5)	24.4619 (9), 7.3737 (2), 12.3961 (4)	4.0462 (1), 20.2165 (6), 11.8058 (3)	23.3058 (11), 5.5770 (2), 8.2847 (4)	7.8897 (3), 9.5581 (4), 16.1101 (5)
β (°)	92.545 (3)	104.639 (2)	115.019 (2)	90.929 (2)	90	96.416 (2)
V (Å^3)	1254.60 (9)	1877.44 (12)	2026.14 (11)	965.59 (4)	1076.82 (8)	1207.26 (8)
Z	4	4	8	4	4	4
D_x (Mg m^{-3})	1.452	1.148	1.404	1.363	1.435	1.464
Radiation type	Mo $K\alpha$	Mo $K\alpha$	Mo $K\alpha$	Mo $K\alpha$	Mo $K\alpha$	Mo $K\alpha$
μ (mm^{-1})	0.11	0.07	0.1	0.09	0.33	0.52
Crystal shape, colour	Rod, yellow	Block, light yellow	Plate, colourless	Lath, colourless	Prism, colourless	Shard, yellow
Crystal size (mm)	0.52 × 0.08 × 0.06	0.40 × 0.35 × 0.30	0.24 × 0.14 × 0.03	0.16 × 0.10 × 0.04	0.20 × 0.15 × 0.10	0.24 × 0.16 × 0.06
Data collection						
Diffractometer	Bruker–Nonius KappaCCD	Bruker–Nonius KappaCCD	Bruker–Nonius KappaCCD	Bruker–Nonius KappaCCD	Bruker–Nonius KappaCCD	Bruker–Nonius KappaCCD
Data collection method	φ and ω scans to fill Ewald sphere	φ and ω scans to fill Ewald sphere	φ and ω scans to fill Ewald sphere	φ and ω scans to fill Ewald sphere	φ and ω scans to fill Ewald sphere	φ and ω scans to fill Ewald sphere
Absorption correction	Multi-scan (based on symmetry-related measurements)	Multi-scan (based on symmetry-related measurements)	Multi-scan (based on symmetry-related measurements)	Multi-scan (based on symmetry-related measurements)	Multi-scan (based on symmetry-related measurements)	Multi-scan (based on symmetry-related measurements)
T_{min}	0.727	0.948	0.913	0.729	0.881	0.849
T_{max}	0.994	0.979	0.997	0.996	0.967	0.970
No. of measured, independent and observed reflections	13532, 2798, 1759	18012, 4315, 2862	16476, 2319, 1733	13634, 2197, 1975	9569, 2143, 1681	16326, 2765, 2133
Criterion for observed reflections	$I > 2\sigma(I)$	$I > 2\sigma(I)$	$I > 2\sigma(I)$	$I > 2\sigma(I)$	$I > 2\sigma(I)$	$I > 2\sigma(I)$
R_{int}	0.083	0.077	0.074	0.049	0.064	0.075
θ_{max} (°)	27.5	27.6	27.5	27.5	27.5	27.5
Refinement						
Refinement on	F^2	F^2	F^2	F^2	F^2	F^2
$R[F^2 > 2\sigma(F^2)]$, $wR(F^2)$, S	0.047, 0.119, 0.99	0.047, 0.122, 1.01	0.048, 0.114, 1.03	0.074, 0.216, 1.17	0.038, 0.085, 1.04	0.040, 0.103, 1.03
No. of reflections	2798	4315	2319	2197	2143	2765
No. of parameters	189	288	152	140	149	161
H-atom treatment	Mixture of independent and constrained refinement	Constrained to parent site	Mixture of independent and constrained refinement	Mixture of independent and constrained refinement	Mixture of independent and constrained refinement	Mixture of independent and constrained refinement
Weighting scheme	$w = 1/[\sigma^2(F_o^2) + (0.0601P)^2]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.0604P)^2 + 0.1466P]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.0555P)^2 + 1.1706P]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.0718P)^2 + 2.0950P]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.0430P)^2]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.0547P)^2 + 0.2206P]$, where $P = (F_o^2 + 2F_c^2)/3$
$(\Delta/\sigma)_{max}$	< 0.0001	< 0.0001	0.001	0.001	< 0.0001	< 0.0001
$\Delta\rho_{max}$, $\Delta\rho_{min}$ (e Å^{-3})	0.23, −0.30	0.21, −0.22	0.19, −0.29	0.42, −0.30	0.20, −0.26	0.38, −0.46
Extinction method	None	*SHELXL*	None	None	None	None
Extinction coefficient	–	0.022 (3)	–	–	–	–

Computer programs used: *DENZO* (Otwinowski & Minor, 1997), *COLLECT* (Hooft, 1999), *SIR*97 (Altomare *et al.*, 1999), *SHELXL*97 (Sheldrick, 2008), *PLATON* (Spek, 2003), *WinGX* (Farrugia, 1999).

be used to prevent sunburn and have been used as sunscreen agents since 1965 (Urbach, 2001). The role of chlorinated benzophenones, such as 4-chloro-2-(3,4,5-trimethoxybenzoyl)phenol (Hsieh *et al.*, 2003) and pestalone (Cueto *et al.*, 2001), as potential anticancer agents and antibiotics has also been examined. In addition, research has been performed on the use of benzophenones as modulators of $GABA_A$ receptors (Kopanitsa *et al.*, 2002).

The molecular structure of benzophenone is influenced by the steric interaction of the two *ortho* H atoms at, *e.g.*, C6 and C13 (Fig. 1) that distort the planarity expected by the π-conjugation of the aryl and carbonyl groups. *Ab initio* studies at the B3LYP/6-311g(D,P) level of theory indicate that the rings in the isolated benzophenone molecule are inclined by approximately 52.1° to one another (Tachikawa & Iyama, 2002) and modelling programs such as *MOPAC* (Stewart, 1999) can be used routinely to estimate theoretical ring twists in substituted benzophenones. Also, subjecting the final atom coordinates from a diffraction study to a *MOPAC* energy-minimization procedure will give an indication of any differences between the X-ray structure and the local energy-minimized structure that may result from packing forces. In the crystalline solid state the additional factors that may need to be considered include classical and non-classical hydrogen bonding, ring–ring ($\pi\cdots\pi$) interactions, X—H$\cdots\pi$ interactions and other non-bonded intermolecular contacts. The current study has examined the crystalline structures of six benzophenones (I)–(VI) and calculated the acute angle between the mean planes through the six atoms of the two aryl rings. This dihedral angle (ω) or ring twist is shown to vary with the substitution on the rings. Dihedral angles between the aryl rings and the central C—C(=O)—C group (ω_A and ω_B) have also been examined as these give valuable information on individual ring conjugations (Gough & Wildman, 1990; Rappoport *et al.*, 1990). Comparisons with other benzophenone crystal structures in the Cambridge Crystal Structure Database (CSD), version 5.28, May 2007 (Allen, 2002) are reported.

The substitution patterns of the six benzophenone crystal structures reported here are given below.



2. Experimental

2.1. Source

The compounds (I)–(VI) were obtained from Avocado Research Chemicals, Lancashire, England and were recrystallized from diethyl ether and petroleum ether (I and III), ethanol (IV and VI), acetone and water (II) and chloroform (VI).

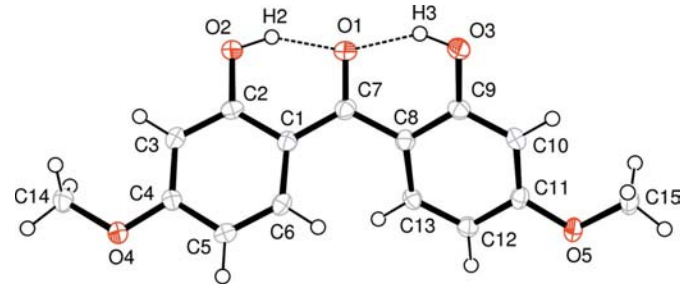


Figure 2
The atomic arrangement in (I), with displacement ellipsoids drawn at the 50% probability level.

2.2. Data collection, structure solution and refinement

The data completeness to θ_{max} ranged from 98.6 to 99.9%. Absorption corrections were applied with *SADABS* (Sheldrick, 2003) for (IV) and *SORTAV* (Blessing, 1997) for (I), (II), (III), (V) and (VI). H atoms were allowed to ride on their attached C atoms with isotropic displacement parameters 1.2 (non-methyl) or 1.3 (methyl) times the equivalent isotropic displacement parameter of the attached atom. The displacement parameters of the hydroxy H atoms were treated in a similar fashion, but the coordinates of these atoms were allowed to refine freely. Further details are shown in Table 1.[1]

2.3. *MOPAC* calculations

MOPAC calculations were performed with CS *MOPAC* Pro™ Version 7 as implemented in *ChemOffice* by Cambridgesoft. The AM1 (Austin Model 1) approximation together with the Hartree–Fock closed-shell (restricted) wavefunction was used and minimizations were terminated at an r.m.s. gradient of less than 0.04 kJ mol^{-1} Å^{-1}.

3. Results and discussion

3.1. Molecular conformations of structures (I)–(VI)

Atomic arrangements in the six benzophenones are shown in Figs. 2–7 and selected molecular distances and angles are shown in Tables 2 and 3.

For (I) a very small twist angle of 37.85 (5)° is observed and there are two intramolecular hydrogen bonds between the hydroxy groups (located at positions 2 and 9) and the carbonyl oxygen. These intramolecular hydrogen bonds result in a long C7=O1 [1.271 (2) Å] bond. When the refined atom coordinates are subjected to a *MOPAC* calculation, the twist angle becomes 52° in the local energy-minimized structure. Clearly the hydrogen bonding and other packing factors influence the

[1] Supplementary data for this paper are available from the IUCr electronic archives (Reference: WS5060). Services for accessing these data are described at the back of the journal.

Table 2
Selected bond lengths and valency angles (°, Å) in (I)–(VI).

Structure	C=O	C1—C7	C7—C8	O1—C7—C8	O1—C7—C1	C1—C7—C8
(I)	1.271 (2)	1.457 (2)	1.473 (2)	117.6 (2)	118.9 (2)	123.4 (2)
(II)	1.235 (2)	1.474 (2)	1.481 (2)	119.0 (1)	119.9 (1)	121.1 (1)
(III)	1.237 (2)	1.478 (2)	1.487 (2)	118.6 (1)	119.5 (1)	121.9 (1)
(IV)	1.230 (4)	1.484 (4)	1.491 (4)	119.7 (3)	119.3 (3)	121.0 (3)
(V)	1.230 (3)	1.490 (3)	1.463 (3)	121.3 (2)	119.0 (2)	119.7 (2)
(VI)	1.233 (2)	1.455 (2)	1.511 (3)	117.3 (2)	123.4 (2)	119.2 (2)

Table 3
Selected torsion and dihedral angles (°) in (I)–(VI).

Structure	O1—C7—C1—C†	O1—C7—C8—C9	ω_A	ω_B	ω
(I)	13.8 (2)	25.0 (3)	14.81 (7)	28.05 (5)	37.85 (5)
(II)	20.3 (2)	25.9 (2)	22.53 (4)	29.60 (6)	49.83 (5)
(III)	−30.3 (2)	−20.9 (2)	32.37 (5)	22.82 (7)	49.84 (5)
(IV)	−26.5 (4)	−27.5 (4)	27.5 (1)	29.6 (1)	51.61 (8)
(V)	45.3 (3)	21.2 (3)	47.4 (1)	24.0 (1)	64.66 (8)
(VI)	3.7 (3)	94.9 (2)	6.5 (1)	84.73 (6)	83.72 (6)

ω_A = dihedral angle between O1,C1,C7,C8 and C1–C6 planes, ω_B = dihedral angle between O1,C1,C7,C8 and C8–C13 planes, ω = dihedral angle between C1–C6 and C8–C13 planes. † C2 for (I), (II), (V) and (VI); C6 for (III) and (IV).

twist-angle value for the molecule in the crystal. The repulsion of H atoms at C6 and C13 is balanced by not only the π-conjugation of the carbonyl and aryl groups, but also by the intramolecular hydrogen bonding. The difference in the C1—C7 = 1.457 (2) Å and C7—C8 = 1.473 (2) Å bond lengths indicates different degrees of conjugation in these Csp^2—C$_{aryl}$ bonds. The dihedral angles that rings *A* and *B* make with the O1,C1,C7,C8 plane (Table 3) are 14.81 (7) and 28.05 (5)°, respectively, and these values also indicate the difference in conjugation of the two aryl rings with the carbonyl group. The small twist angle corresponds to a very short H6···H13 = 2.10 Å separation. Strain in the molecule is also indicated by a quite large C1—C7—C8 = 123.4 (2)° valency angle and a C7 displacement of 0.014 (2) Å from the O1,C1,C8 plane. A similar arrangement of hydroxy groups in 2,2′,4,4′-tetrahydroxybenzophenone (Schlemper, 1982*a*) also results in small twist angles of 42 and 43° for the *Z*′ = 2 structure.

In (II) the ring twist angle of 49.83 (5)° corresponds to an intramolecular H6···H13 = 2.29 Å separation. Again, there are some asymmetrical features associated with this apparently symmetrical molecule. The C1—C7 = 1.472 (2) and C7—C8 = 1.481 (2) Å bonds are similar, but there is a difference in the dihedral angles that rings *A* and *B* make with the O1,C1,C7,C8 plane (Table 3), which are 22.53 (4) and 29.60 (6)°, respectively. The C7=O1 = 1.235 (2) Å bond length is not affected by hydrogen bonding. In this structure one diethylamino group (N2, C18–C21) together with two aromatic C atoms (C10, C11) are disordered over two sites in a 0.74:0.26 ratio. The disordered atoms were restrained to have equal bond lengths and angles. Positional errors, associated with the terminal methyl groups in the lower occupancy conformation, may be underestimated.

The conformation of (III) is similar to (II). The ring twist angle of 49.84 (5)° corresponds to an intramolecular H6···H13 = 2.34 Å separation and the dihedral angles that rings *A* and *B* make with the O1,C1,C7,C8 plane (Table 3) are 32.37 (5) and 22.82 (7)°, respectively. The C7=O1 = 1.237 (2) Å bond length is not affected by hydrogen bonding. [The numbering scheme in (III) and (IV) differs from the other benzophenones to ensure that for each structure examined the substituent groups are on the lowest numbered C atoms.]

In (IV) the C7=O1 = 1.235 (2) Å bond is not affected by hydrogen bonding and the H6···H13 = 2.35 Å separation is related to the ring twist of 51.61 (8)°. The dihedral angles that rings *A* and *B* make with the O1,C1,C7,C8 plane (Table 3) are 27.5 (1) and 29.6 (1)°, respectively.

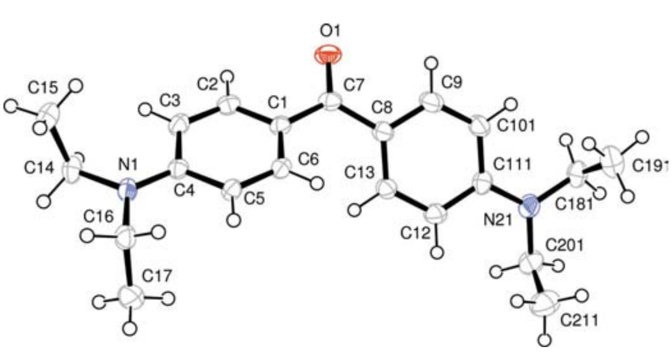


Figure 3
The atomic arrangement in the major component of (II) with disorder removed; displacement ellipsoids are drawn at the 50% probability level.

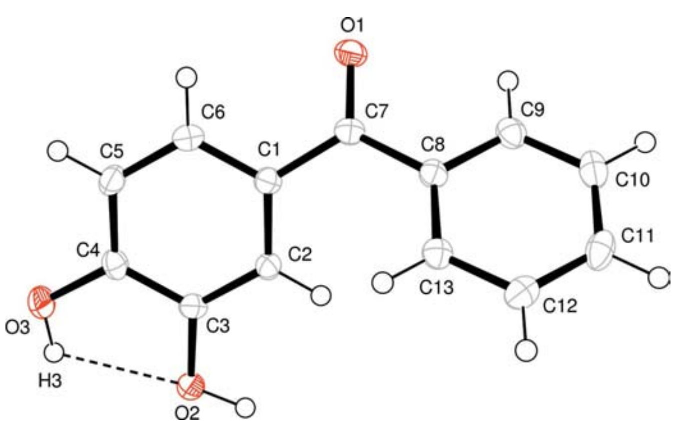


Figure 4
The atomic arrangement in (III), with displacement ellipsoids drawn at the 50% probability level.

Table 4
Hydrogen bonding (Å, °) in (I)–(VI).

Structure	$D-H\cdots A$	$D-H$	$H\cdots A$	$D\cdots A$	$D-H\cdots A$	Motif
(I)	O2—H2···O1	0.92 (2)	1.68 (2)	2.5279 (18)	150.3 (19)	$S_1^1(6)$
	O3—H3···O1	0.92 (2)	1.75 (2)	2.5733 (19)	147 (2)	$S_1^1(6)$
	C3—H3A···O2^{i}	0.95	2.55	3.500 (2)	176	$R_2^2(8)$
	C13—H13···O3^{ii}	0.95	2.45	3.256 (2)	143	$C_1^1(5)$
(II)	C5—H5···O1^{iii}	0.95	2.45	3.3001 (15)	149	$R_2^1(7)$
	C16—H16A···O1^{iii}	0.99	2.41	3.3611 (18)	161	$R_2^1(7)$
(III)	OH—H3···O2	0.94 (2)	2.26 (2)	2.7211 (11)	109 (2)	$S_1^1(5)$
	O2—H2···O1^{iv}	0.94 (2)	1.71 (2)	2.6391 (17)	172 (2)	$R_2^1(6)$
	O3—H3···O2^{v}	0.94 (2)	1.91 (2)	2.8149 (17)	160 (2)	$R_2^2(10)$
	C2—H2A···O1^{iv}	0.95	2.56	3.2309 (18)	128	$R_2^1(6)$
(IV)	O2—H2···O1^{vi}	1.08 (6)	1.66 (6)	2.742 (3)	175 (3)	$C_1^1(7)$
(V)	O2—H2···O1^{vii}	0.85 (3)	1.84 (3)	2.649 (2)	169 (2)	$C_1^1(8)$
(VI)	N1—H1B···O1	0.85 (3)	2.01 (3)	2.666 (2)	134 (2)	$S_1^1(6)$
	N1—H1A···O1^{viii}	0.86 (3)	2.12 (3)	2.932 (2)	158 (2)	$C_1^1(6)$

Symmetry codes: (i) $1-x, 1-y, 1-z$; (ii) $\frac{1}{2}+x, \frac{1}{2}-y, -\frac{1}{2}+z$; (iii) $x, \frac{1}{2}-y, \frac{1}{2}+z$; (iv) $x, -y, \frac{1}{2}+z$; (v) $1-x, y, \frac{3}{2}-z$; (vi) $-\frac{1}{2}+x, \frac{1}{2}-y, \frac{1}{2}+z$; (vii) $x, y, 1+z$; (viii) $1-x, -\frac{1}{2}+y, \frac{1}{2}-z$.

In (V) the dihedral angles that rings *A* and *B* make with the O1,C1,C7,C8 plane (Table 3) are 47.4 (1) and 24.0 (1)°, respectively, and the C1—C7 = 1.490 (3) Å and C7—C8 = 1.463 (3) Å bond lengths are significantly different. The ring twist is 64.66 (8)° with a H6···H13 = 2.69 Å separation.

In (VI) ring *A* is only 6.5 (1)° from the plane of O1,C1,C7,C8, whereas ring *B* is 84.73 (6)° from this plane and this is reflected in the C1—C7 = 1.455 Å and C7—C8 = 1.511 (3) Å bond lengths. In a related compound, 2-amino-2′-chloro-5-methylbenzophenone (Xing *et al.*, 2005), the corresponding dihedral angles are 1 and 85°. The conformation of (VI) also leads to more favourable *ortho* interactions of H6···H13 = 3.54 Å and H6···Cl2 = 3.35 Å. The small dihedral angle involving ring *A* results in an almost coplanar six-membered ring containing the N—H···O bond.

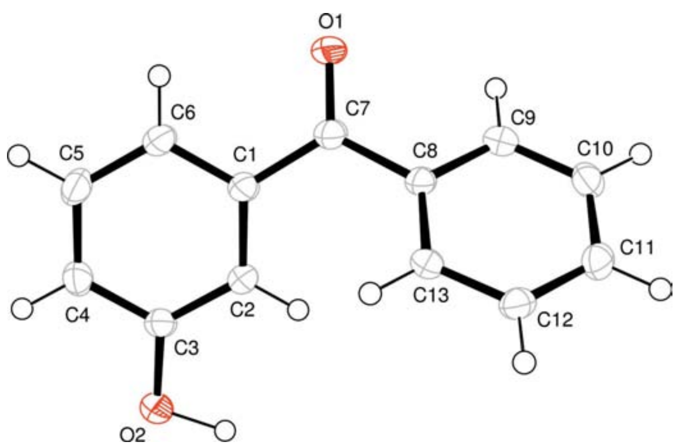


Figure 5
The atomic arrangement in (IV), with displacement ellipsoids drawn at the 50% probability level.

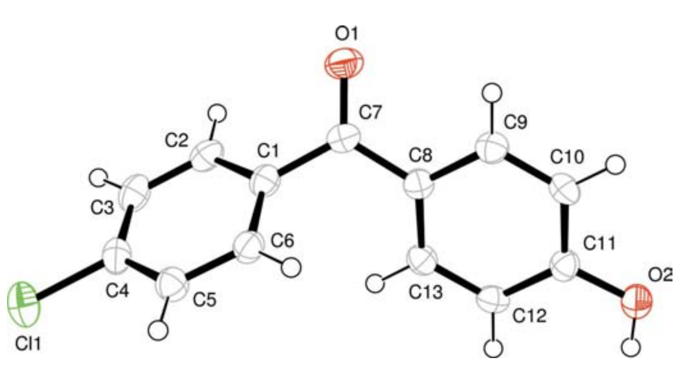


Figure 6
The atomic arrangement in (V), with displacement ellipsoids drawn at the 50% probability level.

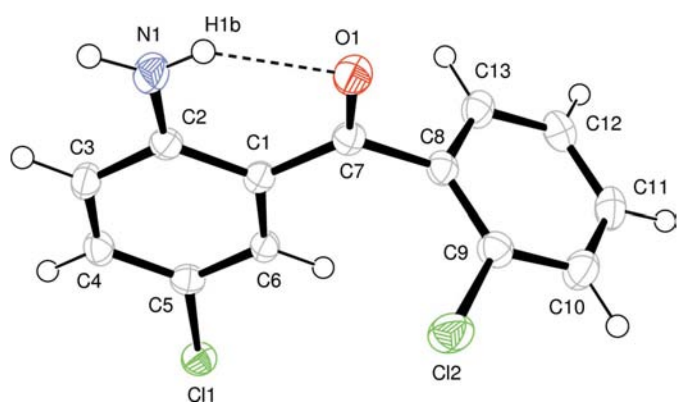


Figure 7
The atomic arrangement in (VI), with displacement ellipsoids drawn at the 50% probability level.

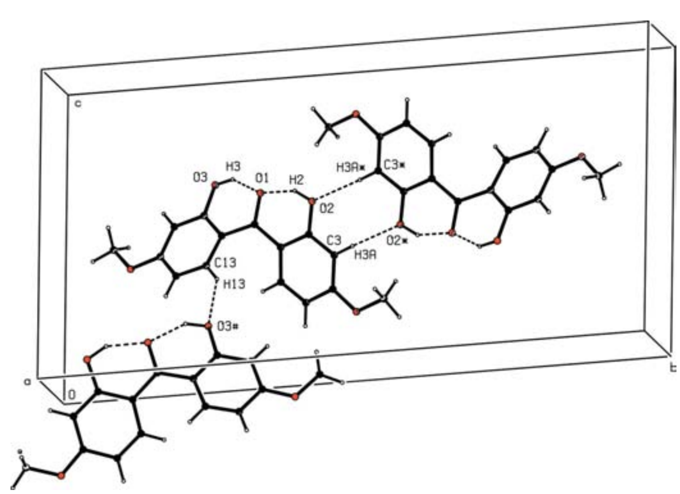


Figure 8
A partial packing diagram for (I). The atoms marked with an asterisk (*) or hash (#) symbol are at the symmetry positions $(1-x, 1-y, 1-z)$ and $(\frac{1}{2}+x, \frac{1}{2}-y, -\frac{1}{2}+z)$, respectively.

The C7 atom is displaced from the O1,C1,C8 plane by 0.024 (2) Å.

3.2. Supramolecular structures of (I)–(VI)

Details of the hydrogen-bond geometry and motifs are given in Table 4 and partial crystal-packing diagrams of the six benzophenones studied are shown in Figs. 8–13.

For 2,2′-dihydroxy-4,4′-dimethoxybenzophenone (I) the carbonyl oxygen links to both hydroxy groups to form two intramolecular $S_1^1(6)$ rings (Table 4). Pairs of molecules are held together by C3—H3*A*···O2 hydrogen bonds that form $R_2^2(8)$ rings and continuous chains are also formed *via* C13—H13···O3 interactions. All these hydrogen-bonding motifs are shown in Fig. 8. The molecule is apparently symmetrical, but interactions involving H atoms induce asymmetrical features.

For 4,4′-bis(diethylamino)benzophenone (II) no classical hydrogen bonding is present and the C7═O1 = 1.235 (2) Å bond is significantly longer than the corresponding bond in (I). The presence of C5—H5···O1 and C16—H16*A*···O1 hydrogen bonding (geometries given in Table 3) results in a single $R_2^1(7)$ ring motif where molecules are linked in pairs as shown in Fig. 9. There is a weak H···π interaction involving

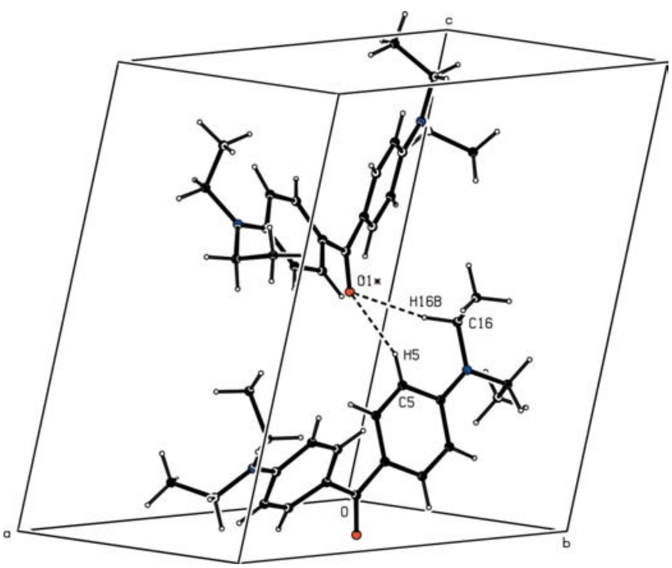


Figure 9
A partial packing diagram for (II). The atom marked with an asterisk (*) is at the symmetry position $(x, \frac{1}{2} - y, \frac{1}{2} + z)$.

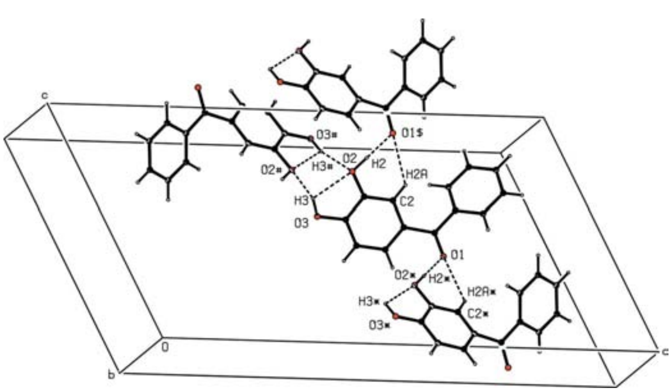


Figure 10
A partial packing diagram for (III). The atoms marked with an asterisk (*), hash (#) or dollar ($) symbol are at the symmetry positions $(x, -y, -\frac{1}{2} + z)$, $(1 - x, y, \frac{3}{2} - z)$ and $(x, -y, \frac{1}{2} + z)$, respectively.

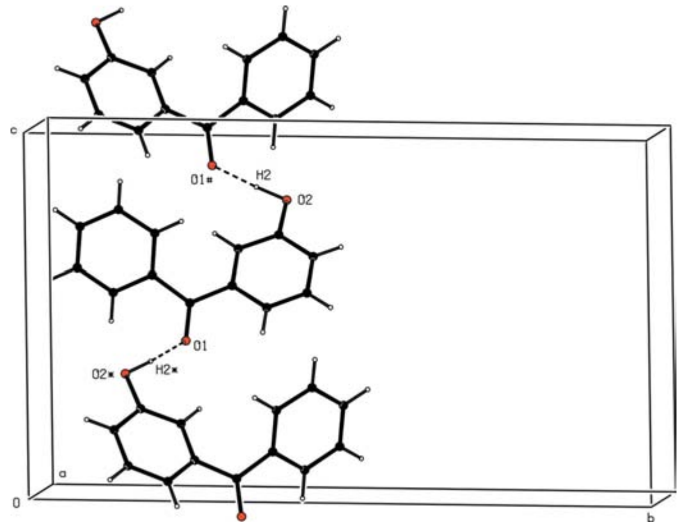


Figure 11
A partial packing diagram for (IV). The atoms marked with an asterisk (*) or hash (#) symbol are at the symmetry positions $(\frac{1}{2} + x, \frac{1}{2} - y, -\frac{1}{2} + z)$ and $(-\frac{1}{2} + x, \frac{1}{2} - y, \frac{1}{2} + z)$, respectively.

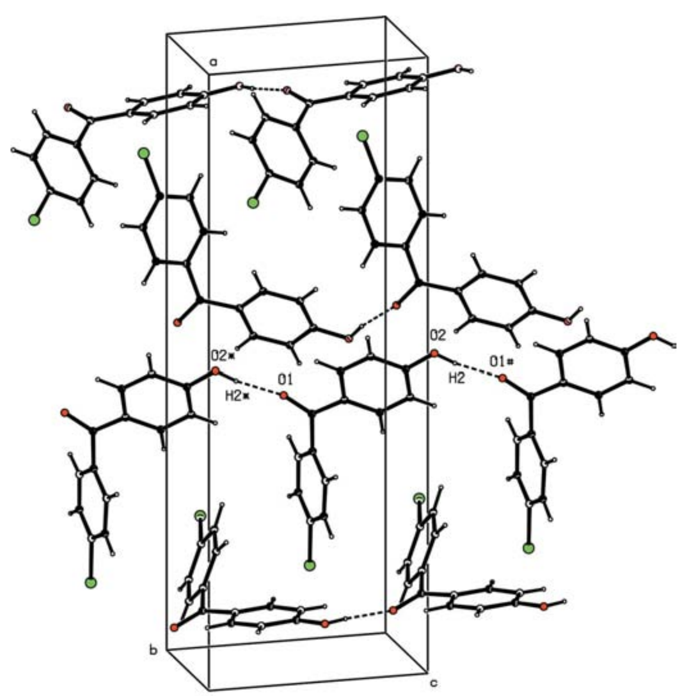


Figure 12
A partial packing diagram for (V). The atoms marked with an asterisk (*) or hash (#) symbol are at the symmetry positions $(x, y, 1 - z)$ and $(x, y, 1 + z)$, respectively.

Table 5
Summary of twist angles and packing considerations.

Structure	Twist angle (°) crystal	Twist angle (°) *MOPAC*	Intermolecular hydrogen bonding	Intramolecular hydrogen bonding	π–π (Ring *A* or *B*)	*X*—H···π (Ring *A* or *B*)
(I)	37.85 (5)	52	C3—H3*A*···O2 C13—H13···O3	O2—H2···O1 O3—H3···O1	None	None
(II)	49.83 (5)	49	C5—H5···O1 C16—H16*B*···O1	None	None	C181—H18*B*···*B*
(III)	49.84 (5)	56	O2—H2···O1 O3—H3···O2 C2—H2*A*···O1	O3—H3···O2	*A*···*A*	C11—H11···*A* C13—H13···*B*
(IV)	51.61 (8)	52	O2—H2···O1	None	None	None
(V)	64.66 (8)	64	O2—H2···O1	None	None	C5—H5···*A*
(VI)	83.72 (6)	83	N1—H1*A*···O1	N1—H1*B*···O1	*A*···*A*	None

the centroid ($Cg2$) of ring B (translated by $1-x, 1-y, z$); here C181—H18B···$Cg2$ = 125° and H18B···$Cg2$ = 2.78 Å.

The hydrogen bonding in 3,4-dihydroxybenzophenone (III) is listed in Table 4 and shown in Fig. 10. Intramolecular hydrogen bonding between hydroxy groups results in a $S_1^1(5)$ ring that forms an intermolecular link to an identical $S_1^1(5)$ ring contained within an $R_2^2(10)$ formation. A further $R_2^1(6)$ ring is formed by the two O2—H2···O1 and C2—H2A···O1 hydrogen bonds. The O2 atom accepts two hydrogen bonds and donates one hydrogen bond and H3, which is attached to O3, is bifurcated with the sum of the three angles about H3 = 360 (3)°. Additional packing features in (III) include a π···π interaction between the A rings where centroids are 4.113 (1) Å apart, the mean planes are separated by 3.423 (1) Å and the offset is 2.280 (1) Å. There is also H···π bonding involving the centroids of rings A ($Cg1$ translated by $\frac{1}{2}-x, -\frac{1}{2}+y, \frac{3}{2}-z$) and B ($Cg2$ translated by $\frac{3}{2}-x, \frac{1}{2}+y, \frac{3}{2}-z$), where C11—H11···$Cg1$ = 122°, H11···$Cg1$ = 2.79 Å; C13—H13···$Cg2$ = 149° and H13···$Cg2$ = 2.75 Å.

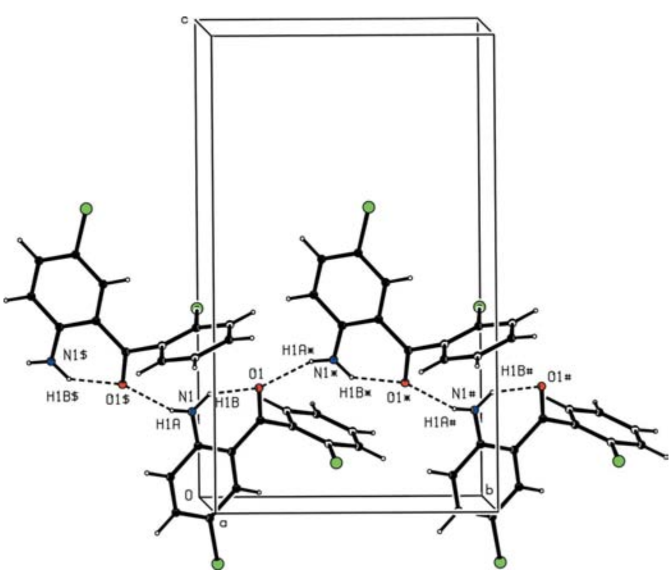


Figure 13
A partial packing diagram for (VI). The atoms marked with an asterisk (*), hash (#) or dollar ($) symbol are at the symmetry positions $(1-x, \frac{1}{2}+y, \frac{1}{2}-z)$, $(x, 1+y, z)$ and $(1-x, -\frac{1}{2}+y, \frac{1}{2}-z)$, respectively.

For 3-hydroxybenzophenone (IV) a single O2—H2···O1 intermolecular hydrogen bond (Table 4) links molecules together in a continuous head-to-tail chain, as shown in Fig. 11.

In 4-chloro-4′-hydroxybenzophenone (V) the hydrogen-bonding scheme is similar to (IV) as again a single O2—H2···O1 intermolecular hydrogen bond (Table 4) links molecules together in a continuous chain, as shown in Fig. 12. In addition there is a weak H···π interaction involving the centroid of ring A ($Cg1$ translated by $\frac{1}{2}-x, y, \frac{1}{2}+z$) as C5—H5···$Cg1$ = 119° and H5···$Cg1$ = 3.32 Å.

In 2-amino-2′,5-dichlorobenzophenone (VI) the amine group is involved in both intra- and intermolecular hydrogen bonding, as listed in Table 4 and shown in Fig. 13. Here the N1—H1B···O1 intramolecular contact forms a $S_1^1(6)$ ring where the hydrogen bond is incorporated into the continuous chain motif formed by the intermolecular N1—H1A···O1 contact. A further packing feature is the π···π interaction between the A rings where centroids are 3.666 (1) Å apart, offset = 1.639 (1) Å and the mean planes are separated by 3.280 (1) Å.

3.3. Comparison of benzophenones (I)–(VI)

A summary of the twist angles in the six benzophenones together with details of intermolecular interactions are shown in Table 5. The torsion angles in Table 4 are all paired in sign and as all space groups except for (V) are centrosymmetric there is no significance to the negative values for (III) and (IV).

Apart from (I) and (III), where intramolecular hydrogen bonding is present, the local energy-minimized conformations obtained from *MOPAC* are very similar to the crystal conformations. The largest twist angle for the six benzophenones is observed in (VI) where there is a short intermolecular separation [Cl2···Cl2^{ix} = 3.3822 (7) Å, and (ix) = atom coordinates transposed by $1-x, 1-y, -z$ compared with a Cl···Cl van der Waal's radius of 3.50 Å (Bondi, 1964)]. Although hydrogen bonding is present in (VI) the twist angle

Table 6
Twist angles (°) in crystal structures of some substituted benzophenones molecules.

CSD CODE Ring position	*R*1 *Ao*	*R*2 *Am*	*R*3 *Ap*	*R*4 *Am*	*R*5 *Ao*	*R*6 *Bo*	*R*7 *Bm*	*R*8 *Bp*	*R*9 *Bm*	*R*10 *Bo*	ω_A *A*	ω_B *B*	ω *A*/*B*
HOFGAK	COOH	H	H	H	H	H	H	CH_3	H	H	80	21	90
CLOHBZ	COOH	H	H	H	H	OH	H	Cl	H	H	89	10	89
QIQCOI	CH_3	H	CH_3	H	CH_3	CH_3	H	CH_3	H	CH_3	52	52	89
BAZYUW	^{i}Pr	H	^{i}Pr	H	^{i}Pr	H	H	OCH_3	H	H	82	15	88
SATKON	^{i}Pr	H	^{i}Pr	H	^{i}Pr	H	COCl	H	H	H	89	11	88
BOBZAC02	COOH	H	H	H	H	H	H	H	H	H	79	9	87
HEXDIX	COOH	H	H	H	H	H	H	Cl	Br	H	79	11	87
QQQHDS10	H	Cl	OH	H	H	COOH	H	H	H	H	15	84	87
SATLAA	^{i}Pr	H	^{i}Pr	H	^{i}Pr	H	H	CH_3	H	H	89	10	87
FOHLEU	OH	H	OH	H	H	COOH	H	H	H	H	5	87	86
GAWHUI	NH_2	H	H	CH_3	H	Cl	H	H	H	H	1	84	85
SATQEJ	^{i}Pr	H	^{i}Pr	H	^{i}Pr	H	H	COCl	H	H	86	7	85
BAZZAD01	^{i}Pr	H	^{i}Pr	H	^{i}Pr	H	H	H	H	H	86	3	84
(VI)	NH_2	H	H	Cl	H	Cl	H	H	H	H	7	85	84
CLHBZL	OH	H	H	Cl	H	COOH	H	H	H	H	2	81	83
RECVUR	OH	H	H	CH_3	H	Br	H	H	H	H	2	82	83
SATKAZ	^{i}Pr	H	^{i}Pr	H	^{i}Pr	H	OCH_3	H	H	H	79	5	83
HECHEC molecule 1	$NHCH_3$	H	H	Br	H	OCH_3	H	H	H	H	1	81	82
SATQAF	^{i}Pr	H	^{i}Pr	H	^{i}Pr	H	H	COOH	H	H	84	6	82
EZOLOU molecule 1	Cl	H	H	H	H	Cl	H	H	H	H	43	51	82
GEQVAZ	COOH	H	NO_2	H	H	H	H	H	H	H	76	11	82
EZOLOU molecule 2	Cl	H	H	H	H	Cl	H	H	H	H	40	51	81
PAMWOQ	Br	H	H	H	H	H	H	H	H	H	68	20	80
BROHBZ	OH	Br	H	H	H	COOH	H	H	H	H	4	81	79
BIMVEZ	Cl	H	H	H	H	H	H	H	H	H	65	20	78
BIMVAV	Cl	H	H	Cl	H	H	H	H	H	H	65	19	78
BIKCOO†	F	F	F	F	F	F	F	F	F	F	48	48	77
HECHEC molecule 2	$NHCH_3$	H	H	Br	H	OCH_3	H	H	H	H	7	72	75
IWOCOM	H	OCH_3	OCH_3	H	H	Cl	H	H	H	H	9	69	75
BIKCII	F	H	F	H	F	F	H	F	H	F	52	30	73
BAGPAA	OH	$COCH_3$	H	CH_3	H	H	H	H	H	H	54	27	71
AMBZAC	NH_2	H	H	H	H	COOH	H	H	H	H	10	64	71
GEQTUR	COOH	H	H	NO_2	H	H	H	H	H	H	62	14	71
REHKEV	OH	H	OCH_3	H	H	H	H	OCH_3	H	OCH_3	3	70	69
DEMBAY	NH_2	H	H	H	H	H	H	H	H	H	19	56	68
YASCUR	H	CH_3	H	H	OCH_3	H	H	H	H	H	56	17	67
KOTBEA	CN	H	H	H	H	H	H	H	H	H	28	45	66
TARZUI	H	Cl	OCH_3	H	OCH_3	H	H	H	H	H	54	16	66
UGECUE	COOH	H	H	H	H	H	H	$N(CH_3)_2$	H	H	64	2	66
(V)	H	H	Cl	H	H	H	H	OH	H	H	47	24	65
BPHENO03 monoclinic	H	H	H	H	H	H	H	H	H	H	29	43	65
TANSEG	H	H	CH_3	H	H	H	H	NH_2	H	H	49	21	64
FINCEK	NH_2	H	H	NH_2	H	H	H	H	H	H	30	39	63
DUDZIL02 polymorph 2	NH_2	H	H	NO_2	H	H	H	H	H	H	20	43	63
FEVNAV01 monoclinic	H	H	CH_3	H	H	H	H	H	H	H	31	38	62
DOBLIP	H	H	H	H	OCH_3	H	H	H	H	OCH_3	27	39	62
UBEDUA molecule 1	OH	OH	OCH_3	H	H	H	OCH_3	OCH_3	OCH_3	H	14	54	61
UBEDUA molecule 2	OH	OH	OCH_3	H	H	H	OCH_3	OCH_3	OCH_3	H	12	55	61
WADBEI	H	H	F	H	H	H	H	NH_2	H	H	46	20	60
AXARAS	OH	H	H	CH_3	H	H	H	H	H	H	12	52	60
NUBDAP	$NHCH_3$	H	H	NO_2	H	F	H	H	H	H	9	53	60
REHJIY	H	CH_3	OCH_3	H	H	H	H	H	H	H	9	53	60
SEZFEJ	H	H	CH_2Br	H	H	H	H	H	H	H	34	31	60
CENSOE	H	H	OH	CH_3	H	H	H	CH_3	H	H	42	24	59
VOFVAN	H	H	H	H	H	H	H	NH_2	H	H	45	19	59
JEDZUO	OH	H	CH_3	Cl	H	H	H	H	H	H	9	52	59
DUDZIL01 polymorph 1	NH_2	H	H	NO_2	H	H	H	H	H	H	20	43	59
FEVNAV02 (trigonal)	H	H	CH_3	H	H	H	H	H	H	H	31	32	57
OLOHIG	OH	H	H	Cl	H	H	H	H	H	H	13	49	57

Table 6 (continued)

CSD CODE Ring position	*R*1 *Ao*	*R*2 *Am*	*R*3 *Ap*	*R*4 *Am*	*R*5 *Ao*	*R*6 *Bo*	*R*7 *Bm*	*R*8 *Bp*	*R*9 *Bm*	*R*10 *Bo*	ω_A *A*	ω_B *B*	ω *A*/*B*
GAWQIF	OH	H	H	CH_3	H	H	Cl	H	H	H	12	51	57
NUVFAL	NH_2	H	H	Cl	H	H	H	H	H	H	2	59	57
KASKIZ	H	H	OCH_3	H	H	H	CH_3	H	H	H	32	29	56
AMBZPH	H	H	NH_2	H	H	H	H	NH_2	H	H	27	36	56
NOPHKN molecule 1	H	H	NO_2	H	H	H	H	NO_2	H	H	35	28	56
MUNQUH	H	OCH_3	OCH_3	OCH_3	H	NH_2	H	H	Cl	H	36	27	56
HAYYAI	H	Cl	OH	H	H	H	H	CH_3	H	H	23	35	55
LEZKIK	H	Cl	NH_2	H	H	H	H	H	H	H	29	30	55
SAJXUW	H	OCH_3	OCH_3	OCH_3	H	H	OH	OCH_3	H	H	34	25	55
TAPVAH molecule 1	H	H	OCH_3	H	H	H	H	H	H	H	34	25	55
TAPVAH molecule 2	H	H	OCH_3	H	H	H	H	H	H	H	21	39	54
TUDNUB	$NHCH_3$	H	H	Cl	H	H	H	H	H	H	15	44	54
PIQLOQ	H	Cl	Cl	H	H	H	H	H	H	H	27	33	54
BPHENO12 orthorhombic	H	H	H	H	H	H	H	H	H	H	29	29	54
NOPHKN molecule 2	H	H	NO_2	H	H	H	H	NO_2	H	H	38	21	54
HEKYOL	H	$COCH_3$	H	H	H	H	H	H	H	H	26	32	53
KEFRAP	OH	H	H	H	H	H	H	H	H	H	11	45	53
WIDTUY†	H	H	OC_2H_5	H	H	H	H	OC_2H_5	H	H	29	29	53
IDAYOC	OH	H	H	CH_3	H	H	H	CH_3	H	H	15	43	53
(IV)	H	OH	H	H	H	H	H	H	H	H	28	30	52
DHXBZP10	OH	H	OH	H	H	H	H	H	H	H	7	47	52
IDIWIC	OH	H	H	CH_3	H	H	H	Cl	H	H	14	43	52
HEQXIL	OH	H	H	Cl	H	H	H	Cl	H	H	15	42	52
MUNRAO	H	OCH_3	OCH_3	OCH_3	H	OH	H	H	Cl	H	41	17	51
FEVMUO01	H	H	CH_3	H	H	H	H	CH_3	H	H	23	35	51
LUDGAS	H	H	$N(CH_3)_2$	H	H	H	H	NO_2	H	H	22	33	51
YAJPUV molecule 1	H	H	OH	H	H	H	H	H	H	H	13	40	51
CBENPH01† *C*2/*c*	H	H	Cl	H	H	H	H	Cl	H	H	28	28	51
GEFMEK	OH	H	H	F	H	H	H	H	H	H	14	40	50
ZZZOVY01†	H	H	I	H	H	H	H	I	H	H	27	27	50
(II)	H	H	$N(Et)_2$	H	H	H	H	$N(Et)_2$	H	H	23	30	50
TICFUG molecule 1	H	H	OH	H	H	H	H	OH	H	H	30	21	50
HMXBZP	OH	H	OCH_3	H	H	H	H	H	H	H	11	43	50
YAJPUV molecule 2	H	H	OH	H	H	H	H	H	H	H	13	40	50
CUZKUD†	H	H	Br	H	H	H	H	Br	H	H	26	26	50
(III)	H	OH	OH	H	H	H	H	H	H	H	32	23	50
CBENPH02† *I*2/*c*	H	H	Cl	H	H	H	H	Cl	H	H	28	28	49
PIQLIK02 monoclinic	H	H	Br	H	H	H	H	H	H	H	22	31	49
PIQLIK03 triclinic	H	H	Br	H	H	H	H	H	H	H	22	31	49
HATXIJ†	H	H	F	H	H	H	H	F	H	H	26	26	49
HMXCBP10	OH	H	OCH_3	H	H	H	H	Cl	H	H	9	42	49
TICFUG molecule 2	H	H	OH	H	H	H	H	OH	H	H	30	21	48
BADVIL10 molecule 1	OH	H	OH	H	H	OH	H	OH	H	H	18	33	43
BADVIL10 molecule 2	OH	H	OH	H	H	OH	H	OH	H	H	19	29	42
(I)	OH	H	OCH_3	H	H	OH	H	OCH_3	H	H	15	28	38

ω_A = dihedral angle between O1,C1,C7,C8 and C1–C6 planes, ω_B = dihedral angle between O1,C1,C7,C8 and C8–C13 planes, ω = dihedral angle between C1–C6 and C8–C13 planes. † $z' = 0.5$.

is related mainly to the steric considerations of the *ortho* Cl atom. When halogens are substituted at *ortho* positions the twist angle is usually large as rotation about the C1—C7 and C7—C8 single bonds relieves steric interactions between the *ortho* substituents at positions 6 (or 2) and 13 (or 9). The twist angle of 83.72 (6)° compares with a calculated value (*MOPAC*) of 83° for the local energy-minimized value on an isolated molecule.

Classical hydrogen bonding is absent for (II) and this is related to its density which is only 1.148 Mg m^{-3} compared with 1.363–1.464 Mg m^{-3} for the other structures (Table 1).

3.4. Comparisons with other benzophenones

Twist angles (ω) have been calculated *via MERCURY* (Macrae *et al.*, 2006) and quoted to the nearest degree from the cif files of a number of substituted benzophenones in the CSD. These are shown in decreasing order in Table 6. The criteria for inclusion was no substituent group larger than three non-H atoms, R not greater than 0.10, no organometallics, no complexes, no solvates and no hydrates. Without these restrictions the number of benzophenone structures in the CSD was 420. Compounds (I)–(VI) are also included in the table. The group labels (R1–R10) used in Table 6 are located on the aryl rings as shown in Fig. 14. Dihedral angles between ring A and the carbonyl plane (ω_A), and ring B and the carbonyl plane (ω_B) are included.

Any consideration of solid-state twist angles in relation to the substitution of the benzophenone molecule has to relate to the packing forces. This is clearly shown by the two polymorphic forms of benzophenone where the twist angle differs by $\sim 11^\circ$ (Table 6). The twist angle is 54° in the orthorhombic form, BPHENO12 (Moncol & Coppens, 2004), and 65° in the metastable monoclinic form, BPHENO03 (Kutzke *et al.*, 2000). Polymorphic forms of 2-amino-5-nitrobenzophenone, DUDZIL01 (Cox *et al.*, 1998) and DUDZIL02 (Cox & Wardell, 2000), both crystallize in space group $P2_1/c$ and have twist angles of 59 and 63°, respectively. Also the polymorphic forms of 4-methylbenzophenone, FEVNAV01 and FEVNAV02 (Kutzke *et al.*, 1996), possess a twist angle that differs by $\sim 5^\circ$. However, the monoclinic and triclinic forms of 4-bromobenzophenone, PIQLIK02 and PIQLIK03 (Strzhemechny *et al.*, 2007), have almost identical twist angles. Also, twist angles in the polymorphic forms of 4,4′-dichlorobenzophenone, CBENPH01 (Granger & Coillot, 1985) and CBENPH02 (Zúñiga & Criado, 1995), are similar. Differences between conformations of identical molecules where Z' is greater than 1 have also to be considered, although in most cases this difference is no more than 2° with the exception of 3-bromo-6-methylamino-2′-methoxybenzophenone, HECHEC (Berger & Bolte, 1994), where the difference is $\sim 7^\circ$. There are also examples of molecular symmetry corresponding to crystallographic symmetry such that when $Z' = 0.5$, the dihedral angles that each aryl ring adopts with respect to the central carbonyl group are identical. When the molecular symmetry does not relate to crystallographic symmetry these dihedral angles can be different.

In relation to Table 6, tentative conclusions may be drawn.

(i) A halogen or carboxylic acid group at any **one** *ortho* position (*e.g.* R1 or R6) leads to high ring twist values [*e.g.* HOFGAK (ω = 90°), GAWHUI (ω = 85°)]. Normally the ring with the group attached is flipped (ω_A or ω_B = 75–90°) with respect to the carbonyl plane and the remaining aryl ring is more conjugated [low (ω_A or ω_B)] with the carbonyl group. This is also shown by variations in the two Csp^2—C_{aryl} bond lengths. Often the carboxylic acid groups are involved in dimer formation, *e.g.* CLOHBZ (ω = 89°), but catemers, *e.g.* QQQHDS10 (ω = 87°), may also form.

(ii) Non-hydrogen-bonding substituents on both *ortho* positions of any one ring (*e.g.* R1, R5) will lead to high ring twist values [*e.g.* BAZYUW (ω = 88°), SATQEJ (ω = 85°)].

(iii) Non-hydrogen-bonding substituents on **one** *ortho* position of **each** ring (*e.g.* R1 and R6) will tend to give poor conjugation for both rings and lead to high ring twist values [*e.g.* QIQCOI (ω = 89°), EZOLOU (ω = 81 and 82°)].

(iv) Substituents (*e.g.* OH, NH_2) in *ortho* positions that form intramolecular hydrogen bonds with the carbonyl oxygen improve conjugation of that particular ring with the carbonyl group [*e.g.* FOHLEU (ω = 86°), DHXBZPO10 (ω = 52°), HMXCBP10 (ω = 49°)].

(v) Two intramolecular hydrogen bonds involving the carbonyl oxygen and *ortho* substituents (at *e.g.* R1 and R6) will give a low ring twist value [*e.g.* BADVIL10 (ω = 43 and 42°)]. In this study the lowest ring twist (ω = 38°) was found for (I) where two intramolecular bonds are present. The structure of 2,2′-dihydroxybenzophenone (Schlemper, 1982*b*) is reported to have ω = 46°, but no structure code is currently available from the CSD.

(vi) Where molecular symmetry corresponds to crystallographic symmetry ($z' = \frac{1}{2}$), then $\omega_A = \omega_B$ [*e.g.* BIKCOO (ω = 77°)]. Where molecular symmetry exists but does not correspond to crystallographic symmetry, then values for ω_A and ω_B may be very similar or may be different [*e.g.* QIQCOI (ω = 89°) and BIKCII (ω = 73°)].

(vii) Substituents in *meta* and *para* positions have less effect on ring twist values than *ortho* substituents, although a *meta* substituent may prevent an *ortho* substituent from hydrogen bonding with the carbonyl oxygen [as in BAGPAA (ω = 71°)]. When both *para* positions are occupied by identical groups and no other substitutions are present there is a tendency for ring twist values to be found in the lower third of Table 6 [*e.g.* TICFUG (ω = 48 and 50°) and HATXIJ (ω = 49°)].

The reason for a somewhat flattened ring (ω_A = 9°) in REHJIY (ω = 60°) is uncertain. The molecule contains a *meta* methyl group and a *para* methoxy group and there is no hydrogen bonding. Only a weak $\pi\cdots\pi$ interaction is present in the crystal. Starting with the X-ray atom coordinates in a *MOPAC* calculation on the isolated molecule leads to a local

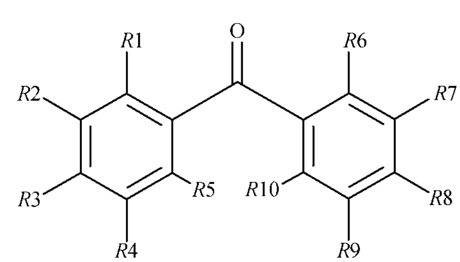


Figure 14
The location of groups (R1–R10) on the aryl rings related to Table 5.

energy-minimized structure with ω_A = 25°, ω_B = 39° and ω = 56°.

When substituent groups consist of several atoms additional factors may need to be considered.

4. Conclusions

The ring twist angle in the stable, orthorhombic form of unsubstituted benzophenone is 54° and the majority of benzophenone molecules in Table 6 (70 out of 98) have higher ring twist values. The lowest ring twist values are associated with hydroxy groups in *ortho* positions forming two intramolecular hydrogen bonds.

2,2′-Dihydroxy-4,4′-dimethoxybenzophenone (I) has the smallest twist angle, 37.85 (5)°, of any benzophenone in Table 6 owing to the formation of two intramolecular hydrogen bonds involving the central carbonyl oxygen. The hydrogen bonds enforce the requirement for planarity due to π-conjugation of the aryl rings with the carbonyl group that is balanced by the unfavourable steric interaction between the *ortho* H atoms at C6 and C13. The substituents on the benzophenones, 4,4′-bis(diethylamino)benzophenone (II), 3,4-dihydroxybenzophenone (III) and 3-hydroxybenzophenone (IV), have little effect on the ring twists [49.83 (5), 49.84 (5) and 51.61 (5)°, respectively] and these values are comparable with the value of 54° found for the orthorhombic form of unsubstituted benzophenone. However, these three values fall within the lower quartile of overall ring twist values in Table 6. Also with respect to (II) other benzophenones substituted only at the two *para* positions by identical groups such as NH_2, NO_2, CH_3, Cl, I, OH, Br and F have similar (ω = 48–56°) ring twist values (Table 6).

4-Chloro-4′-hydroxybenzophenone (V) has a ring twist of 64.66 (8)° which is close to the value of 65° found in the metastable monoclinic form of unsubstituted benzophenone. As in (I), 2-amino-2′,5-dichlorobenzophenone (VI) has a central carbonyl oxygen involved in intramolecular hydrogen bonding with the requirement for a planar $S_1^1(6)$ ring. As there is only one intramolecular hydrogen bond ring *A* is almost coplanar with the central O1,C1,C7,C8 group and the large ring twist of 83.72 (6)° is due to the almost perpendicular orientation of the *B* ring to this central carbonyl group.

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