research papers

Z' = 4 structure without obvious pseudosymmetry: implications for the formation of solid-state compounds

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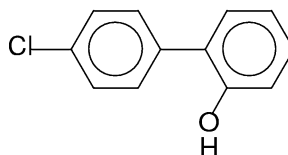
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Crystals of 4-chloro-2′-biphenylol grown at 263 K and studied at both 293 and 142 K are loosely packed and contain OH···O bonded tetramers composed of four crystallographically independent molecules (Z' = 4). Approximate symmetry relationships between independent molecules are apparent in many, perhaps even most, structures with $Z' > 1$, but are not obvious in this structure. The inefficient crystal packing, the surprisingly large value of Z' and the absence of pseudosymmetry reflect the difficulty of finding a dense molecular arrangement that also allows for hydrogen-bond formation. Impediments to good packing are the steric congestion around the *ortho* hydroxyl groups and the difficulty in filling space with significantly twisted biphenyl fragments. The packing arrangement adopted is strongly reminiscent of the structure type found for eight simple 4,4′-biphenyl derivatives, but one of the four independent 4-chloro-2′-biphenylol molecules has an orientation that is significantly different from the orientations of the other three and that does not fit the 4,4′-XPhPhY pattern. It is suggested that molecules that crystallize with $Z' > 1$ are good candidates for solid-state compound formation.

1. Introduction

The structure of 4-chloro-2′-biphenylol (hereafter referred to as 4CL2′OH) was determined as part of a

study of the toxicity of chlorinated biphenyls and, especially, of chlorinated biphenols (Robertson & Hansen, 2001). The structure proved to be very unusual because of the large number of independent molecules (Z' = 4) in the asymmetric unit (Brock & Dunitz, 1994) and because of the lack of approximate symmetry operations relating the independent molecules. When we first started looking at packing diagrams the structure seemed to be just a jumble of molecules, but eventually we saw an analogy with a structure type common for simple 4,4′-disubstituted biphenyls. Three of the independent molecules of 4CL2′OH are arranged in a variant of that structure type; the fourth independent molecule has a quite different orientation. The structural peculiarities (large Z'; lack of pseudosymmetry) appear to result from conflicts between the drive to form OH···O hydrogen bonds and the steric constraints associated with the *ortho* location of the hydroxyl group, and from the problems associated with filling space densely with twisted biphenyl fragments.

Table 1
Experimental details.

	209 K	201 K
Crystal data		
Chemical formula	$C_{12}H_9ClO$	$C_{12}H_9ClO$
Chemical formula weight	204.64	204.64
Cell setting, space group	Monoclinic, $P2_1/c$	Monoclinic, $P2_1/c$
a, b, c (Å)	17.418 (3), 12.015 (2), 19.841 (3)	17.211 (3), 11.962 (2), 19.621 (3)
β (°)	95.59 (2)	95.95 (2)
V (Å^3)	4132.5 (12)	4017.8 (11)
Z	16	16
D_x (Mg m^{-3})	1.316	1.353
Radiation type	Mo $K\alpha$	Mo $K\alpha$
No. of reflections for cell parameters	33 500	20 387
θ range (°)	1.0–25.0	1.0–25.0
μ (mm^{-1})	0.33	0.34
Temperature (K)	293 (1)	142 (1)
Crystal form, color	Pointed laths, colorless	Pointed laths, colorless
Crystal size (mm)	$0.26 \times 0.25 \times 0.05$	$0.41 \times 0.25 \times 0.05$
Data collection		
Diffractometer	Nonius Kappa–CCD	Nonius Kappa–CCD
Data collection method	ω scans with 1.0° steps at $\chi = 55°$	ω scans with 2.0° steps at $\chi = 55°$
Absorption correction	Multi-scan	Multi-scan
T_{min}	0.92	0.87
T_{max}	0.98	0.98
No. of measured, independent and observed reflections	9897, 7262, 4186	11 717, 7080, 4349
Criterion for observed reflections	$I > 2\sigma(I)$	$I > 2\sigma(I)$
R_{int}	0.028	0.052
θ_{max} (°)	25.0	25.0
Range of h, k, l	$0 \rightarrow h \rightarrow 20$	$0 \rightarrow h \rightarrow 20$
	$0 \rightarrow k \rightarrow 14$	$0 \rightarrow k \rightarrow 11$
	$-23 \rightarrow l \rightarrow 23$	$-23 \rightarrow l \rightarrow 23$
Refinement		
Refinement on	F^2	F^2
$R[F^2 > 2\sigma(F^2)]$, $wR(F^2)$, S	0.049, 0.112, 1.16	0.045, 0.080, 0.99
No. of reflections and parameters used in refinement	7262, 510	7080, 522
H-atom treatment	Mixed	Mixed
Weighting scheme	$w = 1/[\sigma^2(F_o^2) + (0.04P)^2]$, where $P = (F_o^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_o^2) + (0.02P)^2]$, where $P = (F_o^2 + 2F_c^2)/3$
$(\Delta/\sigma)_{max}$	0.001	0.001
$\Delta\rho_{max}$, $\Delta\rho_{min}$ (e Å^{-3})	0.30, −0.29	0.331, −0.26
Extinction method	*SHELXL*	*SHELXL*
Extinction coefficient	0.0032 (4)	0.00049 (9)

Computer programs used: *COLLECT* (Nonius, 1999), *DENZO-SMN*, *SCALEPACK* (Otwinowski & Minor, 1997), *SHELXS*97 (Sheldrick, 1997), *SHELXL* (Sheldrick, 1997), *SHELXTL/PC* (Sheldrick, 1990).

2. Experimental

2.1. Synthesis

The compound was synthesized by palladium-catalyzed cross-coupling of 4-chlorobenzene boronic acid and 2-bromoanisole followed by demethylation with boron tribromide (Bauer *et al.*, 1995). Crystals grown at 263 K by slow evaporation of chloroform/*n*-hexane solutions are thin laths with pointed ends. Crystals are thinnest along **a*** and are elongated along **b**. The crystals are colorless initially, but develop a bluish-gray cast over a period of weeks. Oxidation of phenol groups very near the surface of the crystals probably accounts for the color change.

2.2. Structure determination

Structure determination at 142 K and then at 293 K was routine. Two different crystals were used. Hydroxyl protons were located in difference maps; there was no indication of any disorder. The coordinates and U_{iso} values for the four OH protons at 142 K were refined [$r_{O-H} = 0.79$–0.84 (2) Å; $U_{iso} = 0.027$ (8)–0.074 (11) Å^2]; all other protons were constrained to ride on the attached C atom (r_{C-H} 0.95 Å at 142 K and 0.93 Å at 293 K; U_{iso} 1.2U_{eq} for the corresponding C atom). The bond lengths and angles for the OH protons at 293 K were fixed (0.82 Å, 109.5°) and the U_{iso} values determined as for the CH protons, but the four torsion angles (Hn−On−C8n−C7n) were varied. Experimental details can be found in Table 1.[1] Ellipsoid plots of the asymmetric units are shown in Fig. 1 and the crystal packing is illustrated in Fig. 2. All bond lengths and angles are normal; s.u.s at 142 K are 0.003 Å and 0.2°. The change with temperature of the average U_{eq} values is also normal (Dunitz *et al.*, 1988); the values increase by an average factor of 2.1 (1) when the temperature is changed from 142 to 293 K (ratio 2.06).

2.3. Database searches

All searches were run on the April 2001 version (5.21) of the Cambridge Structural Database (Allen & Kennard, 1993; hereafter the CSD).

3. Results

The four independent molecules in 4CL2′OH form a cyclic tetramer (see Fig. 1), a motif that is common for monoalcohols (Brock & Duncan, 1994). The distances at 142 K (see Table 2) within this ring (Etter *et al.*, 1990) suggest that the OH···O bonds between molecules *C* and *D* and between molecules *D* and *A* are somewhat stronger than those between *A* and *B*, and *B* and *C*. The O−H···O angle for the *D*−*A* pair,

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[1] Supplementary data for this paper are available from the IUCr electronic archives (Reference: NS0006). Services for accessing these data are described at the back of the journal.

Table 2
Hydrogen-bonding parameters for 4-chloro-2′-biphenylol.

	O—H	H···O	O···O	O—H···O
At 142 K				
$OA-HB\cdots OA$	0.82 (2)	2.11 (2)	2.899 (2)	164 (2)
$OB-HB\cdots OC$	0.81 (2)	2.11 (2)	2.855 (2)	154 (2)
$OC-HC\cdots OD$	0.79 (2)	1.99 (2)	2.771 (2)	170 (2)
$OD-HD\cdots OA$	0.84 (3)	2.01 (2)	2.756 (2)	148 (2)
At 293 K (H—O—C8—C7 torsions only refined)				
$OA-HA\cdots OB$	0.82	2.15	2.943 (2)	164 (4)
$OB-HB\cdots OC$	0.82	2.14	2.892 (2)	153 (4)
$OC-HC\cdots OD$	0.82	1.98	2.797 (2)	172 (4)
$OD-HD\cdots OA$	0.82	2.07	2.781 (2)	144 (4)

however, is not especially favorable. The OH···O bonds at 293 K seem to be a little weaker than at 142 K.

Molecules A and B are conformational enantiomers of molecules C and D, *i.e.* the senses of the twists in two of the
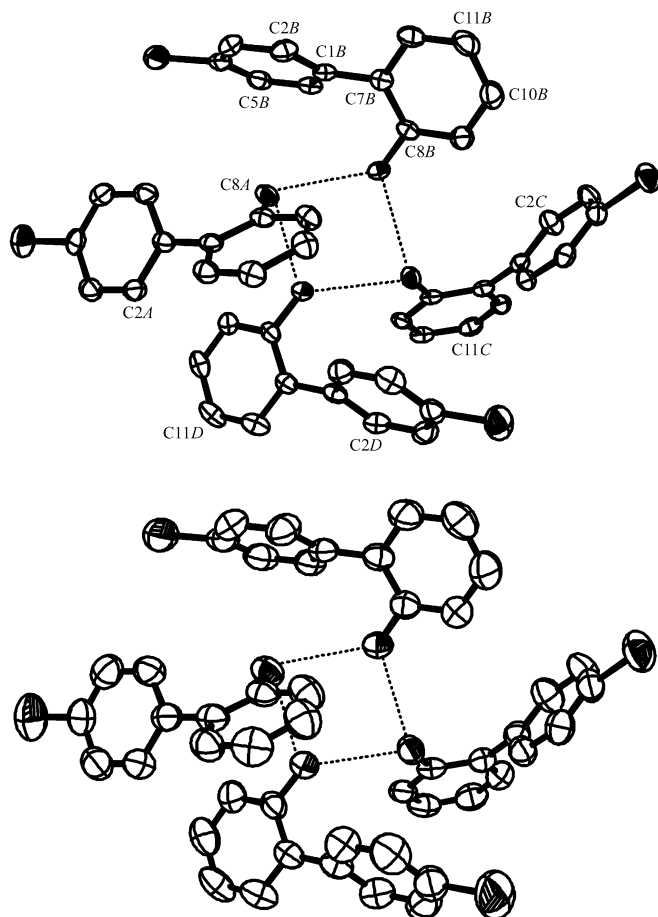

Figure 1
Perspective drawing of the asymmetric unit of 4-chloro-2′-biphenylol at 142 K (upper drawing) and at 293 K (lower drawing). The shapes of the ellipsoids of the non-H atoms correspond to 50% probability contours of atomic displacement. The H atoms have been omitted. Enough of the numbering scheme is shown to define the label of each atom. The C (and attached H) atoms are numbered sequentially around the rings and there are bonds between atom pairs C1n–C7n, C4n–On and C8n–Cln. The last character of the label is the same for all atoms in the same molecule.

molecules of the tetramer (A and B) are opposite from those in the two other molecules (C and D). The magnitudes of the twists in the four molecules can be described by the dihedral angles between the planes of atoms C1n–C6n and C7n–C12n; at 142 K these angles are 48.0, 51.3, 50.6 and 59.5° (s.u.s < 0.1°). Another measure of the twist is the average torsion angle ψ around the central C—C bond (*i.e.* the average of the four angles C2n/C6n—C1n—C7n—C8n/C12n); the ψ values at 142 K for molecules A–D are −48.0 (8), −51.1 (5), 50.6 (5) and 59.2 (3)°. The similarities of the dihedral and torsion angles indicates there is little bending at C1n or C7n. The twist of molecule D is a little larger than the twists of molecules A, B and C, which are nearly the same. There is no important conformational change between 142 and 293 K.

The tetramer in the 4CL2′OH structure is not very pseudosymmetric (see Figs. 1 and 2). While the long axes of molecules A, B and D (the axes defined by atoms Cln, C4n, C1n, C7n and C10n) are roughly parallel (angles 18, −7 and −14° for vectors C04–C10 in molecule pairs A–B, A–D and B–D), the long axis of molecule C has a very different orientation (angles −32, −48 and 39° for molecule pairs A–C, B–C and C–D; all s.u.s < 1°).

The 4CL2′OH structure is very loosely packed. The VOID instruction in *PLATON* (Spek, 2001) gives packing coefficients of 0.65 (Kitaigorodskii, 1961) at 295 K (just 20 K below the melting point) and 0.68 at 142 K; these coefficients are at the low end of the expected range (0.65–0.80; Kitaigorodskii, 1961; Dunitz *et al.*, 2000). At 295 K the average U_{eq} value is 0.068 Å^2 for the C atoms and 0.113 Å^2 for the Cl atoms; the corresponding r.m.s. displacements are 0.26 and 0.34 Å^2. The large U values are consistent with the melting point (314–316 K; this work), which is *ca* 30 K lower than the melting
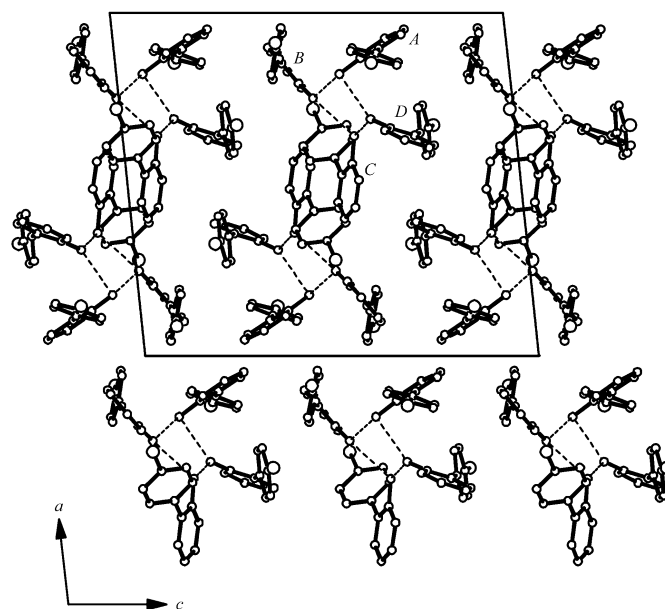

Figure 2
Projection down **b** of the 4-chloro-2′-biphenylol structure.

Table 3
Melting points (K) for some biphenyl derivatives with simple *ortho* and *para* substituents.

Melting point ranges taken from the data in the Beilstein Database (2001). The corresponding range for unsubstituted biphenyl is 339–346 K.

Substituent at 2- or 4-position	Other substituents	T_{fus} (K) for 2-substituted isomer	T_{fus} (K) for 4-substituted isomer	Approximate difference
—F		344–348	344–348	0
—Cl		302–307	349–351	45
—Br		274–275	360–365	90
—I		<298	382–387	120
—CH₃		273	318–324	50
—OCH₃		301–304	359–365	60
—OH		329–334	437–443	110
—CH₂OH		322–324	371–375	50
—NH₂		319–323	323–328	5
—NO₂		307–311	386–391	80
—CN		308–314	357–361	50
—OH	4′-Cl	314–316	418–420	104
—OH	4′-Br	333–334	437–441	105
—OH	4′-I	346–347	466–467	120

Substituents at 2- or 4- position	Other substituents	T_{fus} (K) for 2-ol	T_{fus} (K) for 4-ol	Approximate difference
—OH, —Cl		311–312	353–354	40
—OH, —Cl	4′-Cl	351	389–391	40

point of unsubstituted biphenyl (342–345 K; Sigma-Aldrich Co., 2000).

After studying the structure at 142 K we wondered whether the structure at room temperature (*ca* 30 K above the temperature of crystal growth) might have a smaller, disordered asymmetric unit. There would be ample precedent for such a transition, but none was observed.

4. Discussion

4.1. Packing of 4CL2′OH

The 4CL2′OH molecule, which is both a monoalcohol and a simple biphenyl, has three important packing problems. The first is the steric congestion around the —OH groups; the crowding makes it difficult for a hydroxyl O atom to get close enough to the O atoms of two other molecules (Brock & Duncan, 1994) to form a complete set of OH···O bonds. The second problem is the difficulty of filling space densely with twisted biphenyl fragments. Biphenyls often crystallize with a more planar (and higher-energy) conformation than they would have in the gas phase (Brock & Minton, 1989) because flatter molecules can usually fill space more densely than more twisted molecules (see *e.g.* Gavezzotti, 1990). This space-filling problem is exacerbated when there are *ortho* substituents, because the molecular twist must then be greater than is found for any biphenyl molecules without *ortho* substituents (Brock & Minton, 1989). It is no accident that biphenyl fragments are important building blocks of many liquid crystals (see *e.g.* Baker *et al.*, 1993; see also the comments by Rajnikant *et al.*, 1995, on the crystallization of biphenyls). The third problem is

the rigidity of the molecule; there is only a single low-energy degree of freedom that can be varied to optimize intermolecular contacts.

The observed 4CL2′OH structure can be seen as a compromise arrangement that allows a set of contacts which correspond to rather weak OH···O bonds and that gives acceptably dense packing. The overall arrangement, however, is not very satisfactory, at least as measured by the melting point. The comparison with T_{fus} for unsubstituted biphenyl has already been made; consider also 2-biphenylol, for which the T_{fus} is 15 K higher (see Table 3), even though the structure allows for little OH···O bonding and even though the absence of the Cl atom would be expected to lower the melting point. Note also that there is only one Cl···Cl contact shorter than 4.4 Å [Cl*A*···Cl*B* (*x*, *y* + 1, *z*), 3.808 (1) Å at 142 K] in this structure. The Cl···Cl contacts with lengths < 3.6 Å that might be expected to be present (Desiraju & Parthasarathy, 1989; see also Boese *et al.*, 2001) are missing.

4.2. Packing of some related biphenylols

Compared with 2-biphenylol, 4-biphenylol crystallizes 'normally' in two polymorphic forms ($P2_1/a$, $Z' = 1$ and $P2_12_12_1$, $Z' = 2$; Brock & Haller, 1984), both of which have a full set of OH···O bonds. The room-temperature molecular volume (V/Z) is ~3.4% smaller in the *para* isomer (219.1 and 217.9 Å³ for the two polymorphs) than in the *ortho* isomer (226.3 Å³; Perrin *et al.*, 1987). Moving the substituent to a *para* position greatly reduces the steric congestion that interferes with the formation of OH···H bonds and allows the molecules to adopt a more planar conformation ($\psi < 10°$), which is better for crystal packing. The structure of 3-biphenylol, however, is another high Z' structure; Z' is 6, with two packing units each composed of OH···O bonded trimers (Watkin, 2000). The melting point of 3-biphenylol (349–351 K; Sigma-Aldrich Co., 2000) is intermediate between the melting points of 2- and 4-biphenylol (330–332 and 438–440 K; Sigma-Aldrich Co., 2000).

There are few other comparison structures available in the CSD. Notable is biphenyl-2-methanol (ZENVAP; Rajnikant & Watkin, 1995). ZENVAP differs from 2-biphenylol and 4CL2′OH by having a CH₂ spacer that separates the biphenyl and hydroxyl groups. The additional flexible link makes possible the formation of OH···O chains [basic graph-set symbol $C(2)$] with O···O distances in the range 2.72–2.78 Å. Still, $Z' = 4$, although the four independent molecules in each chain are related by a rather approximate translation and a fairly good screw axis that would be a 2_1 axis if the translation were exact. The important differences between the independent molecules are the molecular twists; absolute values of the torsion angles ψ (see above) are in the range 53.5–61.9 (1)°.

In the CSD there are structures of several more complicated molecules that contain the 2-biphenylol fragment, but that have no other heteroatom that could act as a proton acceptor. None of these structures contain OH···O bonds.

Two other structures from the CSD merit comment. In 2,2′-biphenyldiol (NUTSUQ; $P2_1/c$, $Z' = 1$; Byrne *et al.*, 1998) intra-

and intermolecular OH···O bonds alternate to form chains parallel to **b**. The introduction of the second OH group allows intramolecular OH···O bonding and thus allows spatial separation of the proton donor and acceptor of the intermolecular OH···O bond. This spatial separation relieves the packing problem. Consider also *trans*-(2-*p*-tolyl)cyclohexanol (YELNEI; $P\bar{1}$, $Z' = 2$; Peters *et al.*, 1994), in which the 4-Cl substituent of 4CL2′OH is replaced by a methyl group and the phenol fragment is reduced to a cyclohexanol ring. YELNEI, like 4CL2′OH, forms $R_4^4(8)$ tetramers, but in YELNEI the tetramers are located on inversion centers and the O···O distances (2.73 and 2.82 Å) are more favorable. It is not clear why the cyclohexanol can form more symmetric tetramers than the phenol. The greater thickness and flexibility of the cyclohexyl ring may play a role; examination of van der Waals surfaces of the 4CL2′OH structure suggests that the region around the tetramer is not very densely packed.

4.3. Melting-point comparisons

Melting-point differences for pairs of isomers are good indicators of their relative packing energies. Gavezzotti (1995) has shown that the melting points of *para*-disubstituted
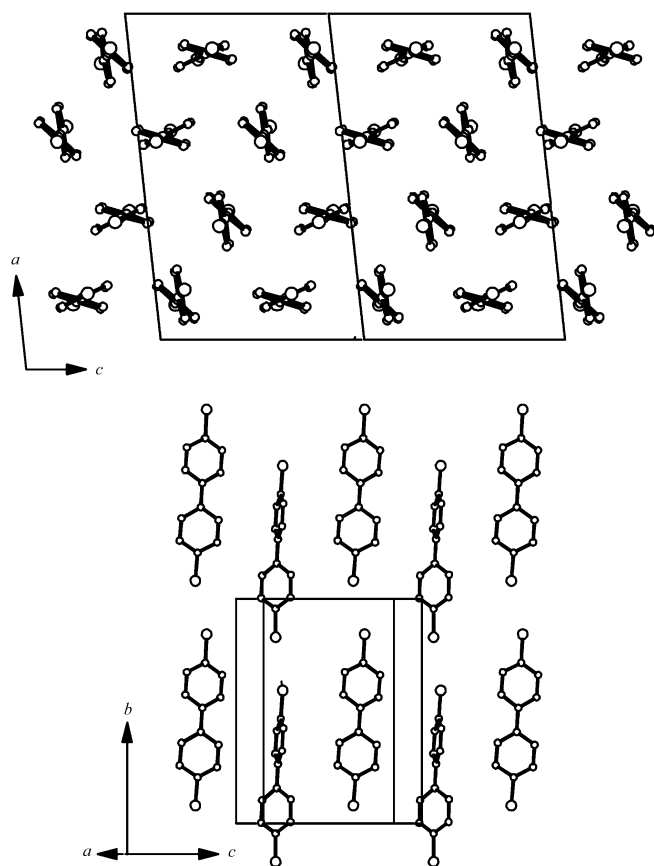

Figure 3
Two projections of the structure of 4,4′-dichlorobiphenyl (Brock *et al.*, 1978). In the upper drawing (projection down **b**) two unit cells are shown so that the projection may be more easily compared with the projection shown in Fig. 2. In the lower drawing (projection down −**a***) a single slice centered around $x = 0.125$ is shown.

benzenes (see also Boese *et al.*, 2001) are systematically higher than the melting points of the corresponding *ortho*-substituted isomers. The differences range from −50 to 150 K, with an average a little above 50 K

Compiling a list of melting points is not so simple (see Gavezzotti, 1995). In the end we decided to use the range of values available in the Beilstein Database (2001) after removing the obvious outliers. The high end of each range is probably more reliable than the low because impurities affect the latter. The ranges are larger for compounds that have been studied by many authors than for compounds that have been mentioned in the literature only a few times.

Table 3 shows that moving a biphenyl substituent from an *ortho* to a *para* position nearly always raises the melting point very substantially, even if the substituent is not involved in OH···O bonding. Moving a fluoro substituent has no effect, but F and H atoms are nearly the same size and the fluoro-biphenyl isomers melt at nearly the same temperature as biphenyl itself (342–345 K). Moving an amino substituent has little effect either, but the melting points for both isomers are unexpectedly low.

The melting-point differences between the *ortho*- and *para*-substituted compounds are at least as large as those seen by Gavezzotti (1995). We believe the melting-point difference reflects the difficulty of filling space densely with molecules having ψ values of 50° or more.

If the effect of hydrogen-bond formation is to be isolated, then pairs of isomers must be located that have an −OH group and a substituent of similar size at positions 2 and 4 of the same phenyl ring. Two pairs of such isomers were found (see Table 3). In both cases the compound with the −OH group in the *para* position has the higher melting point, presumably because that location allows the formation of more favorable OH···O bonds.

Density comparisons cannot be made for the molecules in Table 3, because structures have been determined for only a few of them. Simple biphenyl derivatives crystallize so poorly that systematic studies have been frustrated (Rajnikant & Watkin, 1995; this work).

4.4. Symmetry relationships in alcohol tetramers

In a survey of monoalchohol structures (Brock & Duncan, 1994) we found that many of the $R_4^4(8)$ tetramers were located on $\bar{4}$ sites and that the remainder were located at inversion centers or on a twofold axes. Since that survey, six mono-alcohol structures with $R_4^4(8)$ motifs and $Z' = 4$ have been published, all of them in space group $P2_1/c$, $P2_1$ or $P\bar{1}$. One structure (BAJMOO) has two sets of tetramers, each of which is located on an inversion center. The tetramers in three more of the structures show only small deviations from symmetry 4 (HEGJOS) or $\bar{4}$ (PEZQEQ; SILQEJ); another (YEKBAR) has approximate symmetry 222. The tetramer in the sixth structure (HAVGAM) has an approximate symmetry 2 and very approximate symmetry 2/*m*. The tetramer in a seventh structure (WEYTAV; P1, $Z' = Z = 6$) is nearly centrosymmetric; the other two molecules are disposed almost, but

apparently not quite, centrosymmetrically around that tetramer.[2] Approximate local symmetry seems to be the rule for large Z' structures of monoalcohols and may well be the rule for all structures with large Z'.[3]

4.5. A conjecture about structures with $Z' > 1$[4]

It seems likely that structures with large Z' values are associated with packing conflicts, especially if the structures are not pseudosymmetric (see Desiraju *et al.*, 1991). This conjecture grew out of the observations (Brock & Dunitz, 1994) that $Z' > 1$ structures are unusual and that most molecules that can lie on inversion centers, do. Taken together these generalizations suggest that the size of the asymmetric unit should be minimized. Finally, consider glasses, which have infinite Z' values (or at least Z' values that are too large to measure) and which are often engineered by synthesizing compounds that can be expected to crystallize badly.

The molecule 4-chloro-2′-biphenylol belongs to two classes of compounds (monoalcohols and simple biphenyls with no *ortho* substituent) that have identifiable packing problems (Brock & Duncan, 1994; Brock & Minton, 1989) and that crystallize unusually frequently with $Z' > 1$.

The tendency towards minimization of Z' values, and thus minimization of the volume of the asymmetric unit, may be related to the low incidence of solid-state compound (or co-crystal) formation. Co-crystal formation is rare unless the consituents are enantiomers (inversion symmetry being very favorable for crystal packing) or unless there is a strong donor–acceptor interaction between the two constituents.

4.6. Related structure type

The overall arrangement of molecules *A*, *B* and *D*, as seen in projection down **b**, is very reminiscent of the $P2_1/c$, $Z' = 2$ pattern found for eight biphenyls[5] that have simple subsituents (halo, cyano, methyl, methoxy) in the 4 and 4′ positions. The structures of these eight 4,4′-disubstituted biphenyls are pseudohexagonal (see DCLBIQ10; Brock *et al.*, 1978, which is illustrated in Fig. 3). Projections down **b** of the 4CL2′OH and
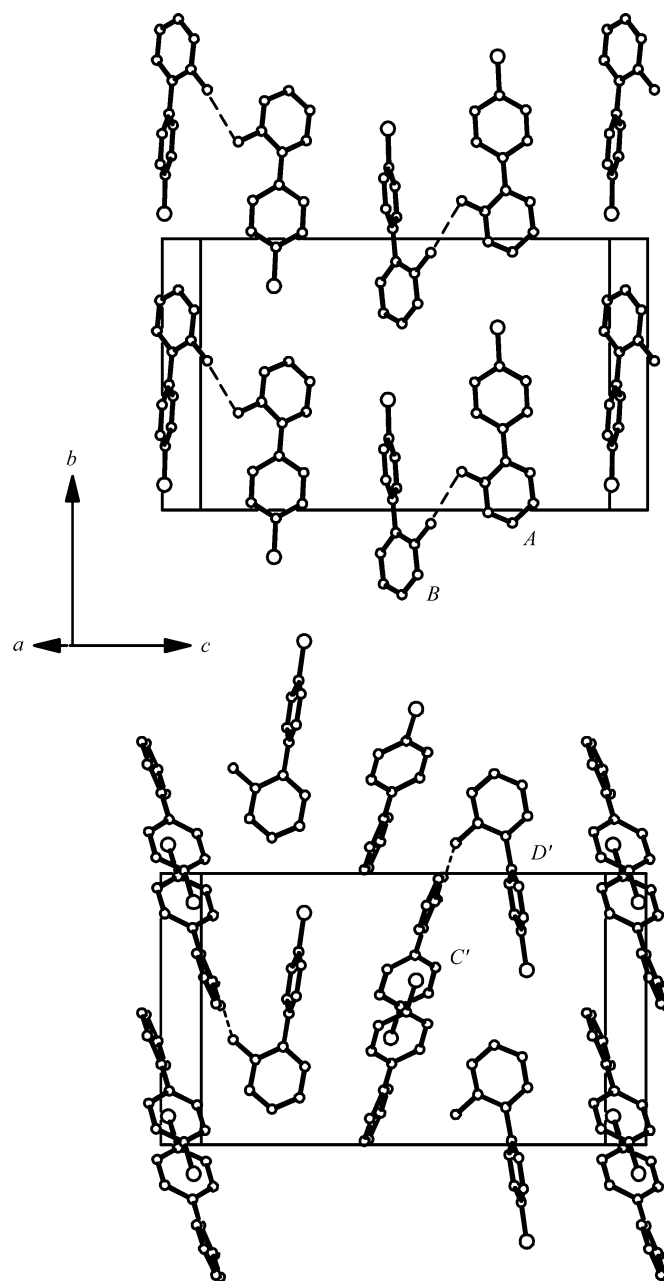

Figure 4
Projections down −**a*** of slices of the structure of 4-chloro-2′-biphenylol. The upper drawing shows a slice centered around $x = 0.875$, and the lower drawing a slice around $x = 0.625$ that also includes the *C* molecules from the slice at $x = 0.375$. Molecules *C*′ and *D*′ in the lower drawing are related to molecules *C* and *D* by the translation **b**.

DCLBIQ10 structures (Figs. 2 and 3) would be nearly superimposable if the long axis of molecule *C* were not tipped so far away from axis **b**. For molecules *A*, *B* and *D* the lines composed of atoms Cl*n*, C4*n*, C1*n*, C7*n* and C10*n* are within 10° of **b**, but for molecule *C* the corresponding line makes an angle of 37° with **b**.[6] These angles change very little with crystal cooling.

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[2] WEYTAV (Rieger *et al.*, 1994) is not listed in Marsh's (1999) compilation of $P1$ structures that should probably be described in a higher-symmetry group.
[3] We know of no systematic study of approximate symmetry, or pseudosymmetry, in all $Z' > 1$ structures, but believe that $Z' > 1$ structures that have identifiable pseudosymmetry occur more frequently than those that do not. The routine determination of structures at low temperatures accounts for some of the pseudosymmetric $Z' > 1$ structures, because transitions with cooling to a larger or lower-symmetry unit cell are fairly common. Some other $Z' > 1$ structures (*ca* 20% of the $P1$ entries in the October 1998 version of the CSD and *ca* 3% of the $C2$ entries in the October 200 release) should probably have been described in higher-symmetry space groups (Marsh, 1999; Marsh & Spek, 2001). Studies of pseudosymmetry in a restricted group of compounds (Britton, 2000) and in specific space groups (Desiraju *et al.*, 1991; Kálmán & Argay, 1998; Marsh, 1999) have appeared.
[4] The class of structures having $Z' > 1$ should also be understood to include structures in which several independent molecules all lie on symmetry elements, even if the apparent Z' value ≤ 1. Consider, for example, the not-uncommon $P\bar{1}$ and $P2_1/c$ structures in which there are two independent molecules, each of which is located on an inversion center. At present there is no distinction in the CSD between such a structure and a more 'normal' structure that has one full molecule in the asymmetric unit.
[5] Refcodes BRCYBP, BTOLYL, DBRBIP, DCLBIQ10, FAZGES01, GAXWAD, JIXBEX and KUSVOJ.

[6] The long axes of molecules *A* and *B* are rotated *ca* 10° about axes that are approximately parallel to **c**, while the rotation of the long axis of molecule *D* is around an axis that is roughly parallel to **a**.

For the eight 4,4′-disubstituted biphenyls the lengths of the **c** axes[7] are in the range 9.42–9.85 Å (all measured at room temperature); in 4Cl2′OH the length of **c** is 2×9.92 Å at 293 K. The corresponding values for **a** are 15.56–16.11 and 17.42 Å. The tilting of molecule *C* causes a small (several %) expansion along **c** and a significant expansion (*ca* 10%) along **a**.

Projections down $-\mathbf{a}^*$ (Figs. 3 and 4) show that the patterns of molecular displacement along **b** are not the same for the two structures and show why **c** is *ca* twice as long in the 4Cl2′OH structure as in the DCLBIQ10 structure. Why are the patterns different? First, the formation of hydrogen-bonded tetramers imposes constraints on the *y* coordinates of the O atoms. Secondly, the 4Cl2′OH molecules, which have only one *para* subsitutent, are 'shorter' than the 4,4′-*X*PhPh*Y* molecules that crystallize in the pseudohexagonal pattern[8] and so cannot fit together in quite the same way.

The 4Cl2′OH structure can be viewed as being formed of two sets of centrosymmetric double layers that are perpendicular to $\mathbf{a}^*$ (see Fig. 4 for pictures of one half of each double layer). The structural importance of those layers is demonstated by the crystal morphology: growth is slowest along **a***. The double layer at $x = 0$ is composed of molecules *A* and *B*, and is very similar to a fragment of the DCLBIQ10 structure (see Figs. 2 and 3). The double layer at $x = 1/2$ is composed of molecules *C* and *D* and looks much less like a fragment of the DCLBIQ10 structure. The contacts at the centers of the two double layers (*i.e.* the contacts at $x = 0$ and at $x = 1/2$) are very different (see Fig. 2).

4.7. Implications for formation of solid-state compounds (or Co crystals)

Co-crystallization is viewed as a route to new solids with potentially interesting properties,[9] but co-crystal formation is uncommon unless the components are enantiomers or interact strongly.[10] It is well known that molecules that crystallize poorly when pure are more likely to give solid-state compounds; this is the basic principle that underlies the field of host–guest chemistry and explains the formation of solvates.[11] Molecules that crystallize poorly can be identified by their melting points and packing efficiencies. We suggest that looking at high-Z' structures, particularly those in which there are no approximate symmetry relationships, might also

be a good way of finding molecules that are likely to form solid-state compounds.

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[7] All cells were transformed to the $P2_1/n$ setting corresponding to that used for 4,4′-dichlorobiphenyl.

[8] The 4,4′-dichlorobiphenyl structure has two sets of short (3.37, 3.38 Å) Cl···Cl interactions that stabilize the molecular columns parallel to **b** of the pseudohexagonal arrangement. There are no Cl···Cl contacts shorter than 3.80 Å in the 4Cl2′OH structure.

[9] See *e.g.* Thaimattam *et al.* (2001) and Desiraju (1989).

[10] It is worth noting that negative deviations from Raoult's Law are rare, even if one component is an organic acid and the other an amine. Segregation of unlike molecules is the rule, even in liquids.

[11] Consider a two-component solid–liquid phase diagram. The lower the freezing point of one of the pure compounds the greater the likelihood of its freezing-point depression curve falling below the melting-point curve of one of the possible solid-state compounds.

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