Structural Studies of Curcuminoids VII. Crystal and Molecular Structure of 1,7-diphenyl-4-propenyl-1,6-heptadiene-3,5-dione

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1,7-Diphenyl-4-propenyl-1,6-heptadiene-3,5-dione, (DPHDD), $C_{22}H_{20}O_2$, $M = 316.4$, crystallises in the orthorhombic space group $Cmc2_1$. The unit cell dimensions are: $a = 21.103(4)$, $b = 11.151(2)$, $c = 7.374(1)$ Å and $V = 1735.38(5)$ Å^3. The calculated density, 1.210 g cm^{-3}, shows four molecules in the unit cell indicating that the molecule exhibits a plane of symmetry.
The X-ray data were collected at low temperature ($T = 121$ K) using Mo Kα radiation ($\lambda = 0.71069$ Å) in measuring the intensities of 864 unique reflections. The structure was refined to a conventional R-factor of 2.98 using 831 reflections with $I > 2.5\sigma(I)$ giving e.s.d. in bond lengths and angles of 0.003 Å and 0.2°, respectively. The present structure is unique relative to the earlier studied curcuminoids in being bisected by a mirror plane, and the position of the enol hydrogen atom is discussed accordingly. The distance between the two oxygen atoms in the enol ring is only 2.423 Å, indicating very strong hydrogen bonding.
The crystal structure is held together by van der Waals' forces only.
The closest interaction between neighbour molecules is found to be between the enol rings, and the position of the oxygen in one ring relative to the –C–(CO)–C– group in the next indicates a nucleophilic interaction.

The title compound (DPHDD) was investigated as a link in the systematic structural study of curcuminoid molecules. These molecules are interesting for several reasons: the geometry of the β-diketo moiety, the resonance properties of the whole molecule, the packing interaction of aromatic moieties, and for the diverse biological activity of these compounds. In spite of the fact that most of the curcuminoid molecules studied are con-figurationally symmetric about the middle atom (C10), the present structure is the first where the molecule is actually bisected by a mirror plane in the crystal phase. A similar situation is, however, reported for other molecules such as bis(m-bromobenzoyl)methane.[1]

Experimental

The compound was synthesised by Dr. Sven-Olov Laweson et al., and provided a few milligrams of yellow prismatic crystals. Intensity data were collected on a SYNTEX P1 diffractometer at liquid-nitrogen temperature. The final unit cell dimensions were determined by a least-squares fit of 15 general reflections with 2θ values of 30–40°. The intensity data collection was monitored by measuring three test reflections in intervals of 135 measurements. No loss of intensity in the test reflections during the experiment was observed. Standard deviations in the measured intensities were calculated as $\sigma(I) = [C_T + (0.02C_N)^2]^{1/2}$, where C_T is the total number of counts and C_N is the scan count minus the background count. The intensity data

were corrected for Lorentz and polarization effects, but not for absorption. The reflection conditions indicated space group $Cmc2_1$ or $Ama2$, both having eight asymmetric units in the cell. However, density measurements indicated four molecules of the title compound per cell, hence the molecule either exhibits a symmetry element or the symmetry observed is in fact pseudo-symmetry. In an effort to settle the question about the symmetry two sets of test data were searched for variation in intensities among reflections in different quadrants. Significant intensity variations indicating pseudo-symmetry were not found. As it appeared to be difficult to solve the structure by using MULTAN, the structure was finally solved in analogy with 4-butyl-1,7-diphenyl-1,6-heptadiene-3,5-dione, a similar molecule which crystallises in a unit cell with dimensions close to those of the present structure.[2] The co-ordinates from this structure were introduced into the unit cell of DPHDD and refined in space group $Pca2_1$ to an R factor of 0.14.

The structure was then adapted to the space group $Cmc2_1$ by shifting the co-ordinates of one half of the molecule half-way along the axes a and b, with weight 0.5 for atoms positioned in the mirror plane. Refinements were performed with least-squares calculations. Hydrogen atom positions, except that of the enol hydrogen atom, were introduced from geometrical considerations and included in the refinements which proceeded with aniso-tropic temperature factors for the heavier atoms and isotropic temperature factors for hydrogen atoms, con-verging at an R-factor of 0.0298, when the enol hydrogen

Table 1. Crystal data and the experimental conditions.

Compound	1,7-diphenyl-4-propenyl-1,6-heptadiene-3,5-dione (yellow)
M.p./K	410
Formula	$C_{22}H_{20}O_2$
Crystal system	Orthorhombic
$a/Å$	21.103(4)
$b/Å$	11.151(2)
$c/Å$	7.374(1)
Cell volume/$Å^3$	1735.3
Experimental temp./K	121
Space group	$Cmc21$ (No. 36)
M/D	316.4
No. of mol. pr. cell (Z)	4 (8 half)
$\lambda/Å$	0.71069 Mo-$K\alpha$
d/g cm^{-1}	1.210
Crystal dimensions	0.4 × 0.3 × 0.6
Apparatus	SYNTEX P1
Scan mode	$\theta/2\theta$
Scan speed/$^\circ$min^{-1}	3.0
Scan range/$^\circ$	1.0–1.2
Background count time	0.7
2θ range	2.5–50.0
No. indep. meas.	864
No. observed [$I > 2.5\sigma(I)$]	831
Test reflections	3
COR	0.02
Corr. for var. in test refl.	0.051, 0.025, 0.010
Corr. for absorption	none
Corr. for sec. ext.	none
Method of structure det.	See text.
Method of refinement	Fourier/LSR
$R = \Sigma \,|F_o| - |F_c|/\Sigma \,|F_o|$	2.98 (ordered: 3.03)
$R_w = [\Sigma w(|F_o| - |F_c|)^2/\Sigma wF_o^2]^{1/2}$	3.48 (ordered: 3.52)
$S = [\Sigma w(|F_o| - |F_c|)^2/(n-m)]^{1/2}$	2.64 (ordered: 2.68)

Table 2. Fractional atomic co-ordinates for DPHDD. Estimates of standard deviations in parentheses.

Atom	x	y	z	U_{eq}[a]
O1	0.0574(1)	0.0584(1)	0.9892	0.0322
C1	0.3640(1)	−0.1744(2)	1.0175(4)	0.0343
C2	0.3169(1)	−0.2439(2)	1.0963(4)	0.0328
C3	0.2543(1)	−0.2088(2)	1.0892(4)	0.0290
C4	0.2370(1)	−0.1011(1)	1.0031(3)	0.0256
C5	0.2852(1)	−0.0319(2)	0.9254(4)	0.0293
C6	0.3482(1)	−0.0679(2)	0.9316(4)	0.0343
C7	0.1719(1)	−0.0574(2)	0.9949(3)	0.0262
C8	0.1196(1)	−0.1099(2)	1.0593(3)	0.0284
C9	0.0575(1)	−0.0529(2)	1.0428(3)	0.0271
C10	0.0000	−0.1135(2)	1.0790(4)	0.0273
C20	0.0000	−0.2403(3)	1.1505(5)	0.0308
C21	0.0000	−0.3379(3)	1.0095(6)	0.0396
C22	0.0000	−0.3238(3)	0.8343(6)	0.0481

Atom	x	y	z	B
HO12	0.020(2)	0.080(3)	0.981(7)	2.5
H1	0.408(1)	−0.198(2)	1.021(4)	3.7
H2	0.329(1)	−0.315(2)	1.154(4)	3.1
H3	0.223(1)	−0.261(2)	1.149(3)	2.7
H5	0.272(1)	0.044(2)	0.867(3)	2.6
H6	0.381(1)	−0.017(2)	0.873(4)	3.8
H7	0.166(1)	0.021(2)	0.934(3)	2.7
H8	0.122(1)	−0.186(2)	1.118(4)	2.4
H20	0.036(1)	−0.253(2)	1.236(3)	2.5
H21	0.000	−0.415(4)	1.057(5)	4.0
H221	0.000	−0.400(4)	0.760(7)	5.5
H222	0.000	−0.248(4)	0.774(6)	4.5

[a] $U_{eq} = (U_{11} + U_{22} + U_{33})/3/Å^2$.

atom was given a disordered position. The experimental conditions are summed up in Table 1.

Computer programs used are described in Refs. 3 and 4.

Description and discussion

The atomic co-ordinates are listed in Table 2, and a drawing of the molecule with the numbering of the atoms is given in Fig. 1. Bond distances and angles are given in Table 3 and selected torsion angles in Table 4.

The properties of the *cis*-enol form of β-diketones have been extensively studied and discussed over the years,[5] and the conclusion seems to be that the energy well for the enolic proton has two minima separated by an energy barrier that decreases as the O–O distance decreases, and that the enolic hydrogen bond is fundamentally asymmetric. On the other hand, the proton may still be observed in a position that is symmetric relative to the two oxygen atoms as reported for the maleate ion[6] where the O–O distance is found to be only 2.393(3) Å. In the present structure, where the O–O distance is the shortest found in the curcuminoids (2.423 Å), a low energy barrier between the two energy minima might be expected. Hence, the

Table 3. Bond lengths (Å) and angles (o) in DPHDD molecules. Estimated standard deviations in parentheses. Bonds involving hydrogen atoms are all within 0.83 to 1.01 Å with e.s.d. 0.03

Bond	$d/Å$	Bond	$d/Å$
O1–C9	1.303(2)	C1–C2	1.388(3)
C1–C6	1.387(3)	C2–C3	1.379(3)
C3–C4	1.406(3)	C4–C5	1.399(3)
C4–C7	1.459(3)	C5–C6	1.389(3)
C7–C8	1.337(3)	C8–C9	1.462(3)
C9–C10	1.413(2)	C10–C20	1.510(4)
C20–C21	1.504(5)	C21–C22	1.303(5)[a]

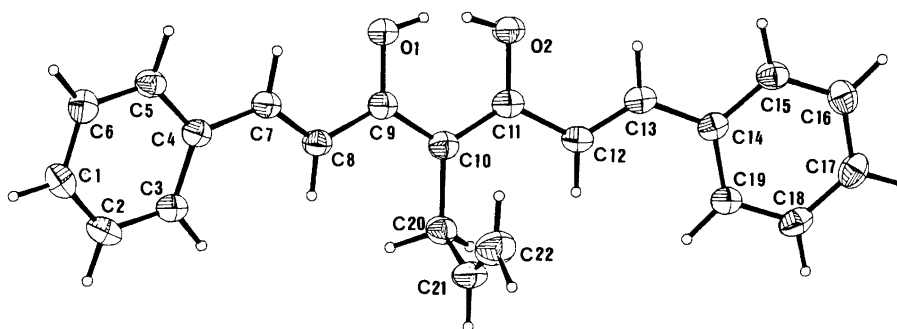| Bonds	$\theta/^\circ$	Bonds	$\theta/^\circ$
C2–C1–C6	119.8(2)	C1–C2–C3	120.8(2)
C2–C3–C4	120.5(2)	C3–C4–C5	117.9(2)
C3–C4–C7	123.2(2)	C5–C4–C7	118.9(2)
C4–C5–C6	121.5(2)	C1–C6–C5	119.5(2)
C4–C7–C8	128.1(2)	C7–C8–C9	121.4(2)
O1–C9–C8	116.1(2)	O1–C9–C10	120.8(2)
C8–C9–C10	123.1(2)	C9–C10–C20	120.9(1)
C10–C20–C21	115.8(3)	C20–C21–C22	126.8(3)

[a] See the text.

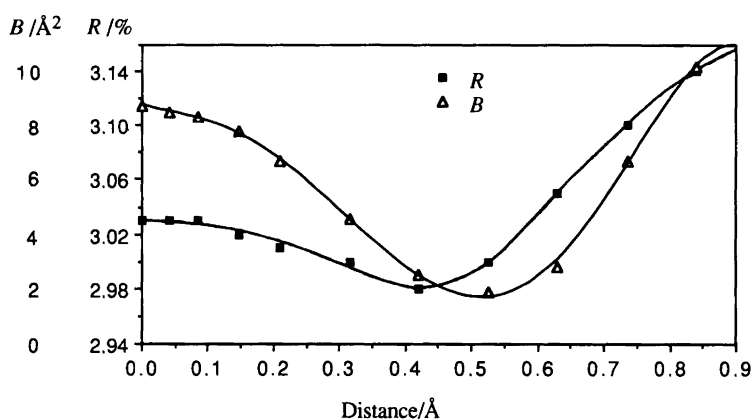*Fig. 1.* Drawing of the DPHDD molecule showing the numbering of the atoms.

Fig. 2. Values of the isotropic temperature factor for the enol hydrogen atom (B) and the R-factor as functions of the distance of the hydrogen atom from the mirror plane bisecting the enol group.

splitting of the enolic group by a mirror plane seemed to indicate a symmetrically positioned hydrogen atom.

However, the mirror plane presents two possibilities for the position of the enol hydrogen atom: in the mirror plane or at statistically displaced positions on each side of the mirror plane. In the last case one would expect an increased vector of the temperature factors along the two C–O bonds, but this could not be detected. On the other hand, calculations of the R-factor and the corresponding isotropic temperature factor for the enol hydrogen atom as this atom is moved in steps from the mirror plane,

Table 4. Torsion angles in DPHDD molecules. Estimated standard deviations in parentheses.

Bonds	θ/°
C3–C4–C7–C8	−1.9(3)
C7–C4–C5–C6	178.9(2)
C4–C7–C8–C9	178.9(2)
C7–C8–C9–O1	−10.6(3)
C7–C8–C9–C10	168.4(2)
C8–C9–C10–C20	4(4)
C9–C10–C20–C21	−89.3(2)

indicate a statistically disordered structure with the hydrogen atom switching between positions 0.42 Å from the mirror plane. The results of the calculations are displayed in Fig. 2, and the geometry of the enol group is depicted in Fig. 3. A Hamilton test[7] on the significance of the R factor indicates that the disordered positioning of the enol hydrogen is the best model.

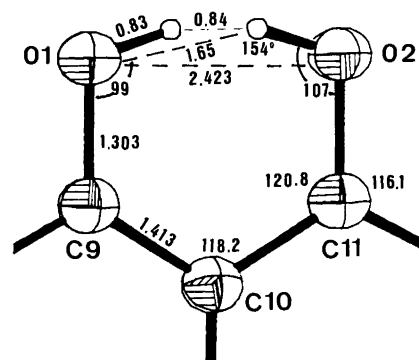A crystallographic study of a deuteriated derivative

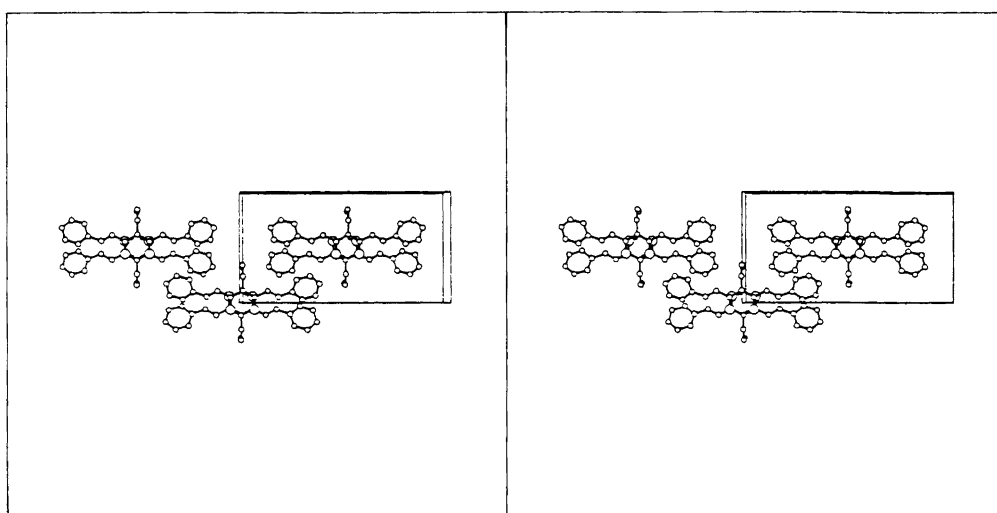*Fig. 3.* Geometry of the enol group with a statistically positioned proton.

511

Fig. 4. Steroscopic view of the packing of the DPHDD molecules as seen down the *c*-axis.

might possibly give more information about the problem discussed above, but an effort to produce such a derivative did not succeed because of lack of material.

Table 3 shows that the refinements using all data produced an unreasonably small value for the C21–C22 bond length [1.303(5) Å]. Refinements of the structure with disordered positions for C21 and C22 did not give a more 'reasonable' description of the geometry of the substituent. However, when refining the structure with high angle reflections (383 refl. with $\sin \theta/\lambda > 0.45$) the bond length was increased by 0.053 Å to 1.355(9) Å whereas the rest of the bonds shifted by less than 0.01 Å. Thus, the positions of one or both of the atoms C21 and C22 seem to be extremely sensitive to the low angle data. As expected, the packing of the molecules is quite similar to that found for DPBHDD.[2] There are no intermolecular hydrogen bonds, and the molecular packing in the crystal seems to be governed mainly by the interaction of

aromatic or pseudo-aromatic moieties. The molecules are stacked in the direction of the *c*-axis as shown in Fig. 4, and the shortest intermolecular distances occur between the O1 (O2) and C11 (C9) in neighbouring molecules (3.29 Å). The interaction is depicted in Fig. 5 where the distances are indicated. The angle between the interacting enol rings is 37.1°. The most interesting feature in this interaction, however, is the position of the oxygen atom relative to the >C–O group. The angle O–C---O is 108.7° and thus the oxygen atom is in a similar position relative to the C–O group as described for nucleophilic O---C=O interactions in other crystal structures.[8] An interaction of this kind should leave the C9 atom slightly out of the plane defined by atoms O1, C8 and C10. Even if such a displacement is not detected as significant in the present study (0.008 Å), it nevertheless seems to be the main determining factor for the molecular packing.

The shortest distance between the phenyl moieties in neighbouring molecules within a stack is found to be 3.597 Å (C4–C5), and the angle between the rings 59.0°.

The contact between different molecular stacks seems to be between an oxygen atom of the enol ring and a C–H group of a phenyl ring (O1–H1, 2.82 Å).

The conjugation throughout the molecule is shown by the bond lengths of the Csp^2–Csp^2 single bonds being close to 1.460 Å (except for the C–C bonds within the enol ring where the bond lengths are closer to aromatic values) and by the $Csp^2 = Csp^2$ double bonds being 1.337 Å, conforming well with the bond lengths for such systems found from X-ray and neutron diffraction data.[9]

The conjugation favours a planar conformation of the molecule as can be seen from Table 4. The small bending of the molecule caused by the torsion angle C7–C8–C9–C10 of 168.4° results in an angle between the phenyl rings of 13.3° and an angle of 13.0° between the enol ring and each phenyl ring.
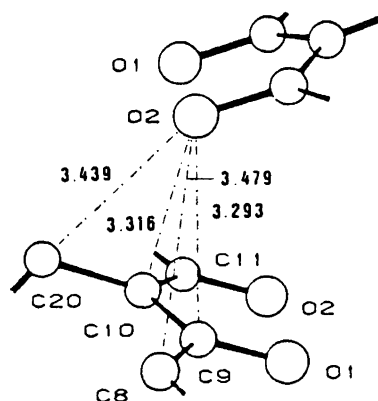

Fig. 5. Geometry of the enol–enol interaction.

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