Crystal Engineering *via* Non-bonded Interactions involving Oxygen. *X*-Ray Crystal Structures of 3,4-Methylenedioxycinnamic Acid and 3,4-Dimethoxycinnamic Acid

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It has been shown that the presence of a methylenedioxy substituent in a planar aromatic molecule tends to favour its crystallisation in highly overlapped structures. Thus, in a series of methylenedioxycinnamic acid derivatives, there is a preference for the β-structure over the α- and γ-forms. It is suggested that this substituent is a good steering device towards the β-form since, in this form, the oxygen atoms of the substituent can participate in stabilising non-bonded interactions involving *p* electrons and further, the compactness of the substituent allows the molecules to crystallise with a 4 Å repeat. The crystal-structure determination of 3,4-methylenedioxycinnamic acid, (1), illustrates these concepts. The crystals of (1) are triclinic, the space group is $P\bar{1}$, $Z = 2$, $a = 3.804(3)$, $b = 10.502(5)$, $c = 11.112(4)$ Å, $\alpha = 77.84(4)$, $\beta = 84.26(9)$, $\gamma = 80.17(5)^\circ$. The structure was solved, not without difficulty, and has been refined to an R-factor of 0.067 on 742 non-zero reflections. Molecules related by translation along [100] are within photoreactive distance and the β-structure leads to the formation of a mirror-symmetry cyclobutane on solid-state irradiation. If the oxygenated substituents are bulky, crystallisation in the β-form is not easy. The crystal structure of 3,4-dimethoxycinnamic acid, (2), demonstrates an alternative packing. Acid (2) is triclinic, the space group is $P\bar{1}$, $Z = 4$, $a = 8.448(3)$, $b = 15.072(8)$, $c = 8.437(6)$ Å, $\alpha = 99.44(5)$, $\beta = 94.71(5)$, $\gamma = 101.59(4)^\circ$. The structure solution was non-trivial and only possible with the use of the program YZARC 80. The structure has been refined to an R-factor of 0.107 on 725 non-zero reflections. Pairs of pseudo-centrosymmetric molecules in the asymmetric unit are hydrogen bonded to form cyclic dimers. Nearest neighbours are related by a pseudo-translation (γ) and centres of inversion (α). Only half the molecules in the structure are potentially reactive; for each of these there are two inversion-related near neighbours. However, only one of these is within photoreactive distance to give the topochemical inversion-symmetry cyclobutane on irradiation.

So varied and subtle are the factors governing the crystal structures of organic compounds that even a minor change in the chemical structure can often result in a considerably different crystal structure. That one or other structure can be achieved for an organic compound need not, however, be an arbitrary matter; in fact a high degree of predictive ability may be gained through manipulation of delicate intermolecular forces. This facet of organic solid-state chemistry has been referred to as crystal engineering and has been actively pursued in recent years.[1]

The general strategy in these efforts is derived from the fact that, for a given organic substance, the manifestation of a directional, though usually weak, intermolecular interaction is often only possible in one of several structural alternatives.[2] The three crystalline forms of substituted cinnamic acids are a typical case in point. While each of the forms, α, β, and γ, consist of strongly hydrogen-bonded dimers, the differences between the three lie in the degree of overlap of the phenyl rings, this overlap being controlled by weaker and more subtle structural features. The β-modification with a repeat axis of *ca.* 4 Å has a considerable ring–ring overlap but such overlap is largely absent in the α- and γ-forms. It is therefore possible to engineer the crystal structure of a cinnamic acid into the β-modification by maximising ring–ring overlap. This approach has worked well with a large number of dichloroaromatic compounds. Not only the dichlorocinnamic acids and their methyl esters, but a large number of planar dichloro-substituted aromatics tend to crystallise with a β-structure.[3]

Non-bonded interactions have been invoked to explain the stability of these overlapped structures.[4] These attractive interactions supposedly involve *p* electrons of the chlorine atoms belonging to molecules adjacent in the stack. If this indeed is the case, other hetero-atom substituents should also show similar effects. The theoretical details have been worked out for fluorine [5] but so far not much attention seems to have been paid to non-bonded interactions involving oxygen atoms. Even though the oxygen atom is smaller than chlorine, it was felt that, *vis-a-vis* dichloro substitution, oxygenated groups constitute a more useful steering device for crystal engineering since the greater reactivity of oxygenated derivatives would lead to two important consequences: (a) chemically closely related compounds, which could be synthesized by similar methods, would also be structurally related, provided the steering group was common to all the compounds, and (b) where crystal structure and solid-state reactivity are related, a large number of compounds would be accessible, in principle, through a few solid-state transformations. For instance, the cyclobutane dimers formed initially on photo-irradiation of *trans*-cinnamic acids could be converted easily into other truxinic or truxillic derivatives by synthetic manipulation of the phenyl rings.

In this study we have explored the crystal chemistry of some *trans*-cinnamic acids with respect to non-bonded interactions involving alkoxy substituents. A noteworthy feature of the cinnamic acids is that there are considerable structural data on the simpler derivatives.[6] Further, those that crystallise in the α- and β-modifications will undergo topochemical solid-state dimerisation on irradiation at *ca.* 300 nm.[7] Since topochemical control in these reactions has been well established, the structure of the photodimer often furnishes a reliable method, independent of *X*-ray crystallography, of establishing the structural type, α or β, of the parent acid. For these reasons, it has been convenient to work mainly with cinnamic acids. However, the non-bonded interactions of the type discussed here are of a completely general nature and should be observed in any planar aromatic molecule.

Table 1. Crystallographic unit-cell parameters for some cinnamic acid derivatives

Compound	Crystals from	a	b	c	α	β	γ	Space group	Z	Crystal packing	Ref.
3,4-Methylenedioxycinnamic acid, (1)	1 : 1 MeOH + acetone	3.804	10.502	11.112	77.84	84.26	80.17	$P\bar{1}$	2	β	8
6-Chloro-3,4-methylenedioxycinnamic acid, (1a)	EtOH	9.05	12.94	4.10	93.3	95.5	74.4	$P\bar{1}$	2	β	9, 10
6-Nitro-3,4-methylenedioxycinnamic acid, (1b)	AcOH	17.91	22.44	3.79	92.2	95.3	94.6	$P\bar{1}$	4	β	11
6-Bromo-3,4-methylenedioxycinnamic acid, (1c)	AcOH	8.83	11.73	4.97	90.6	105.1	84.9	$P\bar{1}$	2	γ	9, 10
6,7-Methylenedioxycoumarin, ayapin, (7)	EtOH (plates)	6.79	18.36	6.50	90	90	90	$Pna2_1$	4	?	11—13
	EtOH (needles)	5.76	18.06	3.87	90	90.1	90	$P2_1$ or $P2_1/m$	2	β	
3,4-Dimethoxycinnamic acid, (2)	1 : 1 MeOH + acetone	8.448	15.072	8.437	99.44	94.71	101.59	$P\bar{1}$	4	α	8
3,4-Dihydroxycinnamic acid, (3)	H_2O	6.711	11.383	5.837	104.99	90.04	103.79	$P\bar{1}$	2	α	14

Experimental

All the cinnamic acids were prepared from the corresponding aldehydes by literature procedures and satisfactorily characterised.[8-14] The data collection for acids (1) and (2) was carried out at the Regional Sophisticated Instruments Centre, Indian Institute of Technology, Madras, and at the School of Chemical Sciences, University of Illinois, Urbana. The computation was carried out at Computer Maintenance Corporation, Hyderabad and at the University of Illinois. The details of the compounds studied and their cell dimensions are given in Table 1.

3,3,4′,4′-Bismethylenedioxy-β-truxinic Acid* (4).—Acid (1) (5 g) was ground finely and irradiated in sunlight for *ca.* 40 h under Pyrex filters. The reaction was monitored by i.r. spectroscopy. Dimer (4) (3.7 g) was separated from (1) on account of its much greater solubility in MeOH. The crude solid was esterified with CH_2N_2 and chromatographed (silica gel, hexane–benzene) to yield the dimethyl ester (5) as a crystalline solid, m.p. 78—80 °C; $\nu_{max.}$ 1 740, 1 495, 1 210, 1 040 cm^{-1}; δ 3.7 (s, 6 H), 4.2 (m, AA′BB′, 4 H), 5.8 (s, 4 H), 6.4—6.6 (m, 6 H). Subsequent alkaline hydrolysis and acidification yielded the pure solid acid, m.p. 179 °C, $\nu_{max.}$ 1 705, 1 500, 1 240, 1 040 cm^{-1}; δ 3.9—4.3 (q, AA′BB′, 4 H), 6.6 (s, 6 H), 5.8 (s, 4 H). The m.s. (10 eV, off resonance) gave *m/z* (%) 384 (0.38) ($M^{+\cdot}$), 268 (6) $(M - C_4H_4O_4)^{+\cdot}$, 192 (100) $(M/2)^{+\cdot}$.

3,3,4′,4′-Bismethylenedioxy-6,6′-dichloro-β-truxinic Acid (4a).—Obtained by a similar solid-state irradiation of acid (1a). The mixture of acids (1a) and (4a) was esterified with MeOH–HCl and the esters separated by column chromatography (silica gel, hexane–benzene). The pure dimethyl ester, (5a), crystallised, m.p. 180—181 °C; $\nu_{max.}$ 1 745, 1 485, 1 250, 1 215, 1 040 cm^{-1}; δ 3.64 (s, 6 H), 4.01, 4.51 (AA′BB′, J_{AB} 7 Hz, 4 H), 5.95—6.02 (q, 4 H), 6.89 (s, 2 H), 6.99 (s, 2 H). The n.m.r. spectrum showed a quartet for the methylene protons of the $-CH_2O_2-$ group, on account of restricted rotation about the single bond joining the phenyl rings to the cyclobutane ring. This is good evidence for a β-truxinic structure. Variable-temperature studies ([$^2H_6$]DMSO) showed that the two lines coalesce to give a single sharp line at about 140 °C. The mass spectrum (10 eV, off resonance) of ester (5a) showed ions at *m/z* (%) 480 (28), 482 (19), 484 (3) all $M^{+\cdot}$, 336 (7), 338 (3), 340 (not detected) all $(M - C_6H_8O_4)^{+\cdot}$. Acid (4a) was obtained routinely from (5a) as a solid; m.p. 255 °C (decomp); $\nu_{max.}$ 1 710, 1 480, 1 170, 1 120, 1 040 cm^{-1}; δ 3.7—4.4 (m, AA′BB′, *J* 8 Hz, 4 H), 6.0 (q, 4 H), 6.9 (s, 2 H), 7.0 (s, 2 H). The m.s. (10 eV, off resonance) gave *m/z* (%) 452 (20), 454 (15), 456 (not detected) all $M^{+\cdot}$ and 336 (21), 338 (13), 340 (not detected) all $(M - C_4H_4O_4)^{+\cdot}$.

X-Ray Structure Determination of 3,4-*methylenedioxycinnamic Acid* (1).—Crystal data, $C_{10}H_8O_4$, $M = 192.2$, triclinic, $a = 3.804(3)$, $b = 10.502(5)$, $c = 11.112(4)$ Å, $\alpha = 77.84(4)$, $\beta = 84.26(9)$, $\gamma = 80.17(5)°$, $V = 426 \times 10^{-26}$ cm^3, $F(000)$ 200, $\mu = 9.46$ cm^{-1} (Cu-K_α), $D_c = 1.50$ g cm^{-3}, $Z = 2$, $D_m = 1.54$ g cm^{-3} (CCl_4–benzene), space group $P\bar{1}$ confirmed during the refinement, Cu-K_α, $\lambda = 1.541\ 78$ Å. Unit-cell parameters were determined by a least-squares fit to the settings for 15 accurately centred high-order reflections. Intensity data were collected on a small crystal 0.3 × 0.1 × 0.06 mm on a computer-controlled Enraf Nonius CAD-4 diffractometer. A total of 742 reflections was considered non-zero at the 3.0 σ significance level out of 1 166 possible re-

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* Truxinic acid, 3,4-diphenylcyclobutane-1,2-dicarboxylic acid.

flections in the 2θ range 3—110°. No absorption corrections were applied and there was no evidence for crystal decomposition. The weights were taken as $1.000/[(\sigma(F_o))^2 + (0.054F_o)^2]$ where $\sigma(F_o)$ is the standard deviation based on the counting statistics. The scattering factors were taken from the expression in reference 15.

The most problematic feature in this structure determination was the presence of an intense reflection (-111) where $F_o = 0.49F(000)$. As discussed elsewhere in this paper, such reflections can lead to erroneous results in the phase determination process because the figures of merit developed by the program are particularly insensitive to the phases of the weaker reflections and these latter phases are the ones that yield critical structural information.

Although the structure was finally solved using the MULTAN 78 program,[16] the correct solution was not obtained by the routine application of either this program or SHELX 76,[17] mainly for the reason mentioned above. When the space-group symmetry was lowered to $P1$, a few peaks were obtained at chemically reasonable positions. Significantly, these peaks formed a centric arrangement and were tentatively assigned to the carboxy-groups. When ten of these peaks (out of a possible 28 in the $P1$ asymmetric unit) were reintroduced in a Karle recycling prior to another run of MULTAN 78 and the E-map computed after the assignment of phases, all but one atom of the structure was revealed. The rest of the structure was obtained by a difference Fourier synthesis. The co-ordinates were then transformed to permit least-squares refinement in the space group $P\bar{1}$. Refinement began at R 0.33 and when positional and anisotropic thermal parameters for all the non-hydrogen atoms were varied, an R-value of 0.124 was obtained.[17] An electron density difference map, at this stage, revealed the position of all ten hydrogen atoms including the carboxy-hydrogen atom. These atoms were included in the subsequent refinements and their isotropic thermal parameters were varied. A few intense low-angle reflections had F_o significantly less than F_c. So, the empirical extinction parameter in the program SHELX 76 was varied and this somewhat improved the agreement between F_o and F_c for these reflections.[17] The final R-value was 0.067 and R_w was 0.079 for 160 refined parameters. When the reflections (110), (101), and (012) were omitted in the refinement, the value for R fell to 0.063 and of R_w to 0.077. The final electron density difference map did not reveal any significant electron density above 0.23 e Å^{-3} or below -0.21 e Å^{-3}. The final atomic co-ordinates for acid (1) are listed in Table 2.

The values of the atomic thermal parameters, tabulations of least-squares planes, and listings of the observed and calculated structure factors for both structures are given in Supplementary Publication No. SUP 23759 (8 pp.).*

Table 2. Atomic co-ordinates in fractional crystal co-ordinates for compound (1) [a,b]

Atom	X/a	Y/b	Z/c
C(1)	0.256 2(13)	0.515 7(5)	0.774 4(4)
C(2)	0.226 9(15)	0.549 3(5)	0.644 3(4)
C(3)	0.275 8(13)	0.670 7(5)	0.587 2(4)
C(4)	0.360 8(13)	0.763 4(5)	0.647 3(4)
C(5)	0.380 6(15)	0.735 5(5)	0.771 7(4)
C(6)	0.337 7(14)	0.612 2(5)	0.833 1(4)
C(7)	0.206 7(14)	0.388 0(5)	0.846 3(4)
C(8)	0.107 0(14)	0.287 9(5)	0.808 2(4)
C(9)	0.068 3(14)	0.164 1(5)	0.890 3(4)
C(10)	0.331 2(20)	0.857 2(6)	0.445 9(5)
O(1)	0.132 2(11)	0.143 1(3)	1.002 2(3)
O(2)	−0.031 3(11)	0.074 7(3)	0.842 6(3)
O(3)	0.406 9(11)	0.877 4(3)	0.564 5(3)
O(4)	0.258 0(11)	0.725 7(3)	0.461 9(3)
H(2)	0.160(13)	0.484(5)	0.606(5)
H(5)	0.489(14)	0.798(5)	0.808(5)
H(6)	0.361(12)	0.579(4)	0.926(5)
H(7)	0.259(13)	0.363(5)	0.930(5)
H(8)	0.033(12)	0.288(4)	0.725(5)
H(10)	0.552(14)	0.881(5)	0.389(5)
H(10′)	0.087(16)	0.906(5)	0.414(5)
H(O2)	−0.064(16)	−0.018(7)	0.914(6)

[a] For labelling of atoms see Figure 3. [b] Estimated standard deviations are given in parentheses.

X-Ray Structure Determination of 3,4-*Dimethoxycinnamic Acid* (2).—Crystal data, $C_{11}H_{12}O_4$, $M = 208.2$, triclinic, $a = 8.448(3)$, $b = 15.072(8)$, $c = 8.437(6)$ Å, $\alpha = 99.44(5)$, $\beta = 94.71(5)$, $\gamma = 101.59(4)$°, $V = 1031 \times 10^{-24}$ cm^3, $F(000)$ 440, $\mu = 0.63$ cm^{-1} (Mo-K_α), $D_c = 1.34$ g cm^{-3}, $Z = 4$, $D_m = 1.30$ g cm^{-3} (CCl_4–benzene), $P\bar{1}$, Mo-K_α, $\lambda = 0.710\,69$ Å. The general procedures for data collection were as described for acid (1). Intensity data were collected (on computer-controlled Enraf Nonius CAD-4 and Syntex P2$_1$ diffractometers) at different times for crystals that were recrystallised independently. The details of the structure solution and refinement were very similar in the two cases and all subsequent discussion refers to the data set collected on the Syntex instrument.[15-17] Intensity data were collected on a small needle 0.4 × 0.1 × 0.03 mm. A total of 725 unique reflections was considered non-zero at the 3.0σ significance level out of 2 925 possible reflections in the 2θ range 3—45°. No absorption corrections were applied and there was no evidence for crystal decomposition. Scan profiles (2θ and ω) indicated that the crystal mosaicity was rather large. The weights were taken as $1.000/[(\sigma(F_o))^2 + (0.045\ F_o)^2]$. In addition to the problems associated with a single very intense reflection, where $F(022) = 0.48F(000)$, the presence of two molecules in the asymmetric unit related by a pseudo-centre of symmetry, the triclinic space group, the poor data quality of the heavily striated crystal, and the limited data set together constituted a formidable obstacle during all stages of the structure solution and refinement. The routine applications of MULTAN 78, MULTAN 80 or SHELX 76 failed to produce even a few peaks that were in chemically reasonable positions. Generally, peaks were found on planes parallel to (022) but within the plane, only a meaningless pattern or sometimes a ‘ chicken-wire ’ pattern was obtained. The strategy, successful in the case of acid (1) of lowering the space-group symmetry did not lead to the correct structure. All attempts to examine the convergence map for weak links and assign a few phases manually resulted in failure. The program YZARC 80 was then used, with 100 reflections in the starting set and the tangent formula being applied for 100 phase sets.[18] E-maps were calculated for the phase sets with the 14 highest combined figures of merit (FOM). These varied from 2.74 to 2.44. The E-maps gave, for the most part, either meaningless fragments or recognisable fragments that did not yield complete molecules on Fourier syntheses. However, one of the sets which although having the lowest residual FOM (16.42) was low down the list in terms of a combined FOM (2.47) gave a complete molecule with chemically reasonable bond lengths and angles.

The positions of the other molecules in the asymmetric unit were determined by isotropic refinement and difference Fourier syntheses in the space group $P1$. It was not possible to develop the structure in $P\bar{1}$ at this point. A total of 3.5

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* For details of the Supplementary Publications Scheme see Instructions for Authors (1984), *J. Chem. Soc., Perkin Trans. 2*, 1984, Issue 1.

molecules was obtained in stages and the R value was 0.25. Significantly, strong correlations were obtained for the positional and thermal parameters of many atoms belonging to molecules that were not hydrogen bonded (molecules 1 and 4 in Figure 6). This clearly shows that the centre of symmetry is *not* located at the centre of the hydrogen-bonded dimer ring but is rather found between pairs of these dimers. The molecular parameters of the symmetry-independent molecules were, however, such as to suggest that they were related by a pseudo-centre of symmetry.

The co-ordinates were appropriately transformed prior to refinement in the space group $P\bar{1}$. After the initial refinement cycles had established the pseudo-centre of symmetry, further refinement was carried out on only a single molecule at a time. Generally, either the positional or thermal parameters, but not both, were varied. These parameters changed markedly and unacceptably for several atoms and had to be fixed or adjusted as appropriate before they could be allowed to vary again. Owing to the generally unfavourable observation-to-parameter ratio and the other problems already described, the fluctuations and irregular behaviour of several atoms were ascribed to limited data rather than to any inherent fault in the model chosen. In the penultimate cycles, the positional and anisotropic thermal parameters of all the non-hydrogen atoms [except C(4) and C(3′)] were varied in turn. The hydrogen atoms (U = 0.07 for Me hydrogens) were placed in calculated positions. In the final refinement cycles, the positional parameters of both molecules (80 refined parameters) were varied together with R being 0.107 and R_w 0.136. The final difference density map did not reveal any significant peaks above 0.44 e Å^{-3} or below −0.46 e Å^{-3}. The final atomic co-ordinates for acid (2) are listed in Table 3. The values of the thermal parameters and of the structure factors are in the Supplementary Publication.

The high value of R and the erratic behaviour of some of the atoms during the refinement are surely related to the several problems associated with this structure. Clearly the unorthodox refinement procedure could have led to errors in the final molecular parameters, but the packing, relative molecular orientation, and close contacts of molecules that are potentially photoreactive in the solid state are all undoubtedly correct.

Results and Discussion

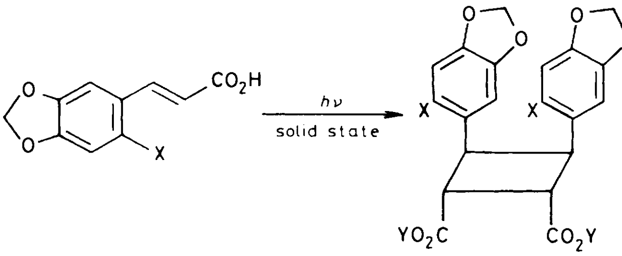
Crystal Engineering.—Of the 36 crystalline *trans*-cinnamic acids examined by Schmidt, 13 have alkoxy substituents. Yet only three, the 2-ethoxy, the 2-bromo-5-methoxy, and the 2-chloro-5-methoxy derivatives crystallise with the β-structure.[6,7] Further, the first two are polymorphic with the β-modification metastable while in the third, the presence of a chlorine atom perhaps renders the β-form stable. Clearly the β-form is not the favoured one for these simple alkoxycinnamic acids even though the oxygen atoms could, in principle, participate in stabilising non-bonded interactions. The only reason for this observation could be a steric factor. Groups such as methoxy and ethoxy are probably too bulky to be properly accommodated in a 4 Å unit cell because repulsive non-bonded interactions between hydrogen atoms in these groups render the β-structure energetically unfavourable.

Table 3. Atomic co-ordinates in fractional crystal co-ordinates for compound (2) [a–c]

Atom	X/a	Y/b	Z/c
C(1)	0.283(2)	−0.357(1)	0.098(2)
C(2)	0.328(2)	−0.282(2)	0.022(3)
C(3)	0.221(2)	−0.233(1)	−0.022(3)
C(4)	0.053(0)	−0.262(0)	−0.011(0)
C(5)	0.012(2)	−0.331(2)	0.070(3)
C(6)	0.120(2)	−0.385(1)	0.124(3)
C(7)	0.408(2)	−0.404(1)	0.144(2)
C(8)	0.395(2)	−0.471(1)	0.227(3)
C(9)	0.543(2)	−0.512(2)	0.270(3)
C(10)	0.410(2)	−0.123(1)	−0.134(3)
C(11)	−0.228(2)	−0.243(1)	−0.046(3)
O(1)	0.510(2)	−0.584(1)	0.332(2)
O(2)	0.677(1)	−0.475(1)	0.241(2)
O(3)	0.244(1)	−0.157(1)	−0.099(2)
O(4)	−0.046	−0.204	−0.045
H(2)	0.457	−0.261	−0.002
H(5)	−0.119	−0.352	0.089
H(6)	0.078	−0.446	0.178
H(7)	0.525	−0.376	0.107
H(8)	0.273	−0.506	0.247
H(10)	0.415	−0.063	−0.194
H(10)$_1$	0.455	−0.175	−0.213
H(10)$_2$	0.494	−0.100	−0.023
H(11)	−0.297	−0.193	−0.078
H(11)$_1$	−0.254	−0.261	0.065
H(11)$_2$	−0.265	−0.305	−0.144
H(O)	0.613	−0.615	0.371
C(1′)	1.141(2)	−0.783(1)	0.546(3)
C(2′)	1.103(2)	−0.860(1)	0.623(3)
C(3′)	1.221(0)	−0.905(0)	0.669(0)
C(4′)	1.385(2)	−0.871(1)	0.620(3)
C(5′)	1.427(2)	−0.797(1)	0.553(3)
C(6′)	1.310(2)	−0.751(2)	0.513(3)
C(7′)	1.015(2)	−0.734(1)	0.491(3)
C(8′)	1.033(2)	−0.659(1)	0.430(3)
C(9′)	0.892(2)	−0.618(2)	0.389(3)
C(10′)	1.034(2)	−1.007(2)	0.773(3)
C(11′)	1.655(2)	−0.903(2)	0.642(3)
O(1′)	0.920(1)	−0.550(1)	0.317(2)
O(2′)	0.754(1)	−0.656(1)	0.423(2)
O(3′)	1.192(1)	−0.979(1)	0.731(2)
O(4′)	1.482(0)	−0.926(0)	0.688(0)
H(2′)	0.975	−0.866	0.642
H(5′)	1.554	−0.770	0.536
H(6′)	1.336	−0.692	0.447
H(7′)	0.890	−0.767	0.510
H(8′)	1.151	−0.629	0.398
H(10′)	1.023	−1.064	0.833
H(10′)$_1$	1.005	−0.948	0.857
H(10′)$_2$	0.943	−1.022	0.668
H(11′)	1.734	−0.938	0.692
H(11′)$_1$	1.703	−0.829	0.665
H(11′)$_2$	1.647	−0.924	0.504
H(O′)	0.817	−0.518	0.285

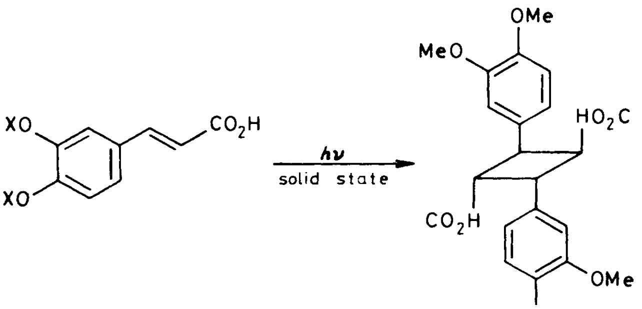
[a] For labelling of atoms see Figure 5. [b] Estimated standard deviations for non-hydrogen atoms are given in parentheses. [c] Unprimed atoms belong to molecule 2. Primed atoms belong to molecule 4.

On the other hand, in a planar compound such as (1) that contains the methylenedioxy group, the substituent group is compact and planar. The oxygen atoms may therefore participate in stabilising non-bonded interactions of the type referred to above without there being an adverse steric factor. A compound such as acid (1) is expected to and indeed does crystallise in a single modification with a β-structure (short axis 3.803 Å). This form was the only one obtained from a large number of solvents and the structure was confirmed through the identification of the dimer (4) obtained by solid-state irradiation, as 3,3,4′,4′-bismethylenedioxy-β-truxinic acid. The mass spectrum of dimer (4) shows a peak at m/z 268 (M − $C_4H_4O_4$)$^{+\cdot}$. This peak originates from unsymmetrical cleavage of the cyclobutane ring and is characteristic of the mirror symmetric β-truxinic acids. The structure of acid (1)



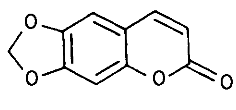
(1) X = H
(1a) X = Cl
(1b) X = NO_2
(1c) X = Br

(4) X = H, Y = H
(4a) X = Cl, Y = H
(5) X = H, Y = Me
(5a) X = Cl, Y = Me



(2) X = Me
(3) X = H

(6)



(7)

was also confirmed, not without difficulty, by an *X*-ray structure determination.

That the effect of the methylenedioxy group is more general and not merely restricted to acid (1) is shown in Table 1 where unit-cell parameters of a number of related compounds are given. It should be noted that both the 6-chloro acid (1a) and 6-nitro acid (1b) crystallise with the β-structure, while in the case of the bromo acid (1c) the size of the bromine substituent does not permit crystallisation in this structure notwithstanding the 'β-steering' methylenedioxy group. The β-structure for acid (1a) was confirmed by mass spectroscopy on the dimer (4a) as outlined previously. Following the same trend. 6,7-methylenedioxycoumarin, ayapin, (7), which contains the same steering group and has a planar structure, crystallises in two forms, one of which has a 4 Å repeat.

It is instructive to compare the above values with the cell parameters of 3,4-dimethoxycinnamic acid, (2), and 3,4-dihydroxycinnamic acid, (3). If the bulk of a single methoxy group is sufficient to steer the crystal structure of a cinnamic acid away from the β-form, then it should certainly be expected that acid (2) should crystallise in a form other than β. This acid crystallises with a short axis of 8.437 Å and on solid-state irradiation yields the corresponding α-truxillic acid, (6), which was characterised from its mass spectrum. There is no possibility of unsymmetrical cleavage of the cyclobutane ring here and no peak at $M - 116$ was observed. Yet, the crystal structure of acid (2) is complex. The number of molecules in the asymmetric unit is two and the structure determination revealed that this was, in effect, a structure where both α- and γ-types of overlap were present. Satisfyingly, however, the β-overlap cannot be seen here.

The crystal structure of acid (3) (short axis 5.837 Å) is currently under investigation. Hydrogen bonding between –OH groups or between –OH and C=O groups as in 4- and 3-hydroxycinnamic acids, respectively, may be important here.[19,20] The pair of acids (1) and (2) could conceptually be the intermediates in the unambiguous syntheses (using appropriate alkylation and dealkylation procedures) of β-truxinic and α-truxillic dimers of acid (3). These dimers can therefore be prepared without foreknowledge of the crystal structure and consequently of the solid-state reactivity of acid (3) itself. Unless (3) were at least dimorphic (α and β), the dimer acids cannot be obtained by direct solid-state topochemical photoaddition reactions. Thus crystal engineering could be employed to synthesize compounds which cannot be normally achieved through other means.

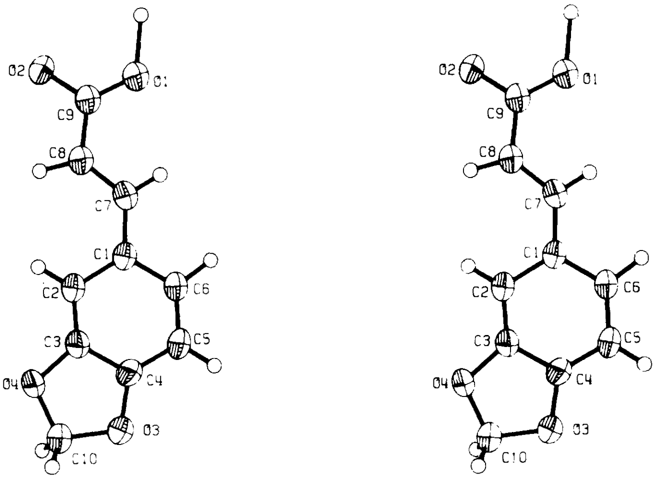


Figure 1. Stereodrawing of a single molecule of acid (1)

Crystal Structure Analyses.—The structure determination of acid (2) was fraught with several problems already described. The presence of a single reflection whose observed structure amplitude is extremely large and comparable to the magnitude of $F(000)$ tends to prove troublesome in direct methods, but its downweighting or complete removal prior to the phasing process for acids (1) and (2) did not lead to the correct structure in these cases.

A single very intense reflection (*hkl*) in a triclinic space group clearly indicates that the molecules crystallise in sheets parallel to the plane (*hkl*). In several attempts to solve the structure of acids (1) and (2), the presence of such reflections led to two results: (a) most of the peaks in the *E*-map tended to lie in the plane (*hkl*) or in planes parallel to it but the arrangement of peaks within the plane bore no resemblance to the correct structure. In other words, the phase determination led to the obvious conclusion that the atoms lie in a plane that is parallel to (*hkl*). Information about the arrangement of atoms in the plane (which should have originated from the weaker relationships in the convergence map) tended to be obscured by the stronger relationships involving the reflection (*hkl*); (b) the molecule could be identified and had the correct orientation but it was misplaced with respect to the centre of inversion. If weak phase relationships give information about the molecular fragment, even weaker

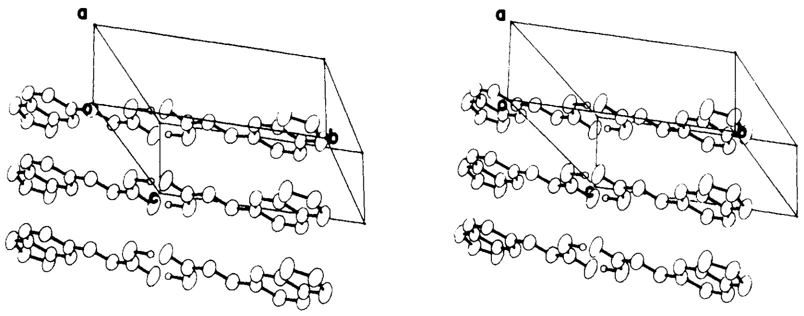


Figure 2. Stereodrawing of the packing of (1) showing centrosymmetric dimers stacked along [100]. Molecules adjacent in the stack are potentially photoreactive in the solid state

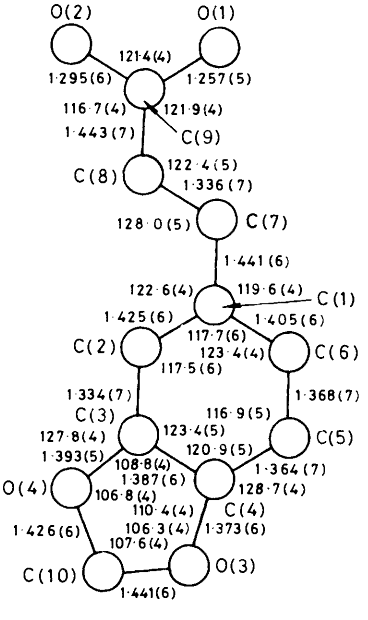
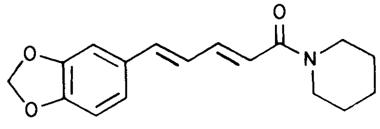
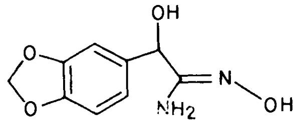


Figure 3. Bond lengths and angles (with e.s.d.s) for (1)



(8)



(9)

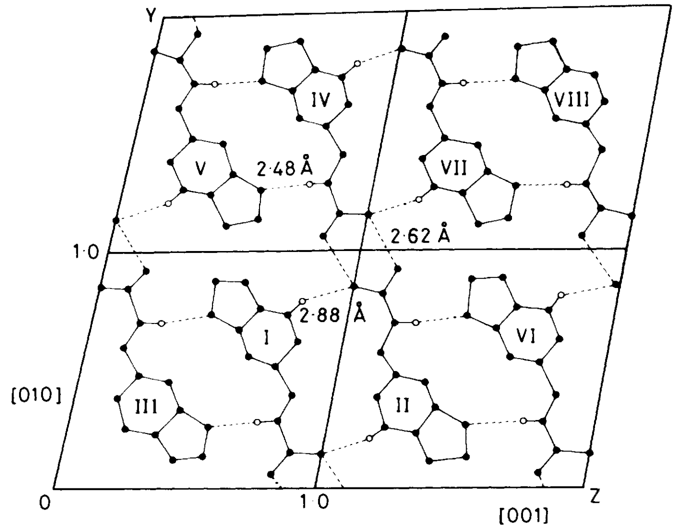


Figure 4. Projection of the crystal structure of (1) down [100]. Molecules located on a sheet parallel to $(1\bar{1}\bar{1})$ are shown. Molecule code: I x,y,z; II $1-x, 1-y, 2-z$; III $-x, 1-y, 1-z$; IV $1+x, 1+y, z$; V $1-x, 2-y, 1-z$; VI $1+x, y, 1+z$; VII $2-x, 2-y, 2-z$; VIII $2+x, 1+y, 1+z$

relationships would decide the position of these fragments in the unit cell and these weaker relationships would almost certainly have been ignored in the assignment of phases.

The superiority of YZARC 80 over MULTAN 80 and SHELX-76 should be noted, with respect to its ability in handling the sheet-like structure of acid (2). Even though the program could not locate the position of the molecule in the unit cell, it was able to identify the correct molecular fragment and this was impossible with the other programs. This is a result of using a much larger starting set in the phase determination process and with it a larger number of phase relationships.

Molecular and Crystal Structure of Acid (1).—Figure 1 shows the stereoview of the single molecule while Figure 2 gives the packing of the molecules. The bond lengths and angles are shown in Figure 3. In the crystal structure of acid (1), the molecules exist as centrosymmetric hydrogen-bonded dimers with the O–H ··· O distance being 2.619(5) Å. This value is quite close to the value of 2.630 Å for the similar separation in α-*trans*-cinnamic acid [21] and the distances of 2.614, 2.632, 2.645, and 2.65 Å in *p*-methoxy,[21] *p*-hydroxy,[19] *p*-methoxy,[19] and *m*-hydroxycinnamic [20] acid, respectively. The two C–O bond distances, C(9)–O(1) and C(9)–O(2) and the angles O(1)–C(9)–C(8) and O(2)–C(9)–C(8) indicate partial disorder of the carboxy-group by the exchange of the carboxyl oxygen and hydroxy groups. This type of disorder is a familiar one and quite common in the crystal structure of carboxylic acids,[22] but is only slight in this case.

The other intramolecular distances and angles have values typical of those found in the crystal structures of related compounds. Characteristic features include the expanding of the angle C(1)–C(7)–C(8) to 128.0(5)° and of C(7)–C(1)–C(2)

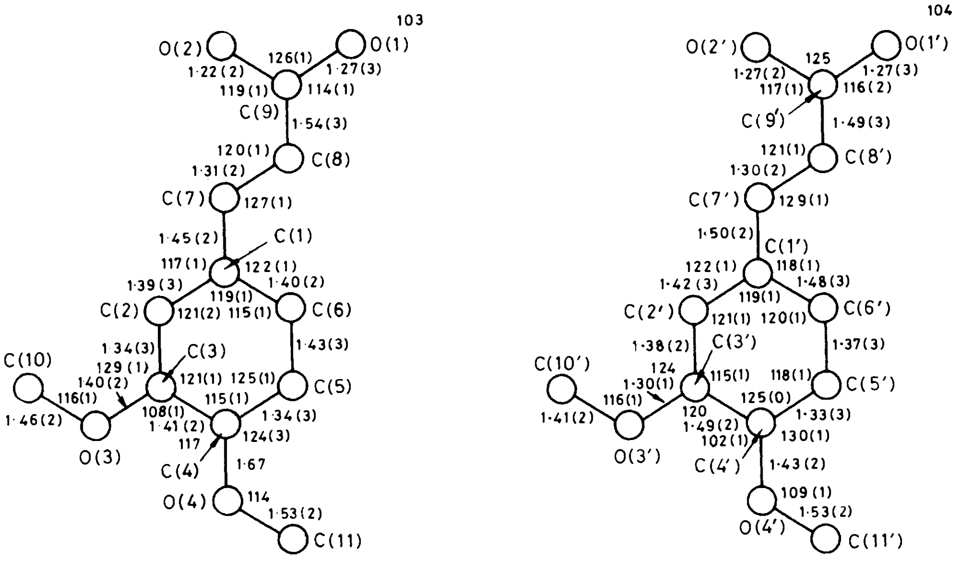


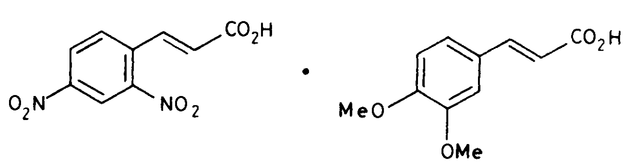
Figure 5. Bond lengths and angles (with e.s.d.s) for (2)

to 122.6(4)° to minimise steric interaction. The C–C bond lengths in the phenyl ring are curiously quite different from one another but all of them are close to the corresponding values in the crystal structures of the alkaloid piperine, (8), and the substituted amide oxime, (9), both of which contain the 3,4-methylenedioxyphenyl moiety.[23,24] There is the same elongation of C(1)–C(2) to 1.425(6) Å [1.415 Å in (8) and 1.398 Å in (9)], a contraction of C(2)–C(3) to 1.334(5) Å [1.364 Å in (8) and 1.371 Å in (9)] and contractions of C(1)–C(2)–C(3) and C(4)–C(5)–C(6) to 117.5(4)° and 116.9(5)°, respectively [116.7 and 116.9° in (8) and 117 and 117° in (9)]. Observed C–H bond distances range from 0.94(5) to 1.04(6) Å with a mean value of 1.00 Å. The carboxy O–H distance is 1.14(7) Å.

The molecular conformation can be defined in terms of three planes in a manner similar to the analysis of other cinnamic acid structures by Bryan and Freyberg:[21] (*a*) the phenyl ring, (*b*) the four-atom olefin linkage C(1)–C(7)–C(8)–C(9), and (*c*) the four-atom carboxy group. Details of these planes are given in the Supplementary Publication. The dihedral angles between the planes are: *ab*, 4.56, *bc*, 0.8, and *ac*, 5.4°. The values show that as in the case of other cinnamic acids whose structures have been determined, the solid-state conformation of acid (1) is closely planar but can be more accurately defined in terms of three rigorously planar units.

Since acids (1) and (2) are unsymmetrically substituted with respect to the C(1)–C(4) axis, there are two distinct conformations possible around the C(1)–C(7) single bond. In the structure of (1), H(2) and H(8) are adjacent rather than H(6) and H(8). This latter conformation is seen in the crystal structure of acid (2). The conformational preference in these structures is a subtle matter and is probably determined by weak intermolecular forces.

In the crystal structure of acid (1), the hydrogen-bonded dimers lie in sheets parallel to (−111) where *F*(−111) corresponds to the strong in-phase diffraction already mentioned. Within a sheet, the dimers are associated through C–H ··· O short contacts as illustrated in Figure 4. Notably, H(8)(*x*,*y*,*z*) ··· O(4)(−*x*, 1 − *y*, −*z*) is 2.48 Å while H(5)(*x*,*y*,*z*) ··· O(1)(1 − *x*, 1 − *y*, 2 − *z*) is 2.88 Å. This kind of sheet-like structure may be seen in the crystal structure of methyl 3-nitro-4-hydroxycinnamate.[25] The sheets themselves are stacked along (100) so that potentially photoreactive molecules are related by a translation along *a* and the spacing between the reactive double bonds is nearly 3.8 Å (Figure 1). Thus the product of solid-state topochemical dimerisation is an *m*-symmetry cyclobutane.



(10)

Molecular and Crystal Structure of Acid (2).—Figure 5 gives the bond lengths and angles in the two symmetry-independent molecules. Owing to the small data set, high crystal mosaicity, and problems in the refinement, the molecular parameters in the crystal structure of acid (2) are of only limited accuracy. However, the general trends are in accord with those found in the crystal structures of other *trans*-cinnamic acids. For the most part, the bond lengths and angles are within 3σ of the more accurate values reported for the 3,4-dimethoxycinnamic acid molecule in the crystal structure of its 1 : 1 complex, (10), with 2,4-dinitrocinnamic acid.[26]

The molecular parameters of both molecules in the asymmetric unit are very similar, indicating that the pseudo-centre of symmetry is very nearly a true centre and therefore explaining the strongly hypercentric distribution of normalised structure factors. Within the limits of the analysis, the C–O distances in the carboxy groups are equal, thus indicating the same type of rotational disorder that is present in acid (1).

The 3,4-dimethoxyphenyl fragment is quite planar and resembles several related compounds recently analysed by Caillet.[27] According to this report, there is a marked tendency for *ortho*-dimethoxyphenyl compounds to adopt a planar conformation in the solid state so that steric repulsions between molecules may be minimised. Details of several planes in the structure of acid (2) are given in the Supplementary Publication.

The crystal structure of acid (2) is complicated, in marked contrast to acid (1). There are two molecules in the asymmetric unit and these are hydrogen-bonded to form pseudo-centrosymmetric dimers. Thus in Figure 6, molecules 2 and 4 (x, $1 + y$, z) form a dimer ring centred at approximately (0.716, 0.434, 0.329) while molecules 1 and 3 ($1 - x$, $-y$, $1 - z$) are related to these by a centre of symmetry. So molecules 1 and 2 are, in effect, related by a pseudo-translation.

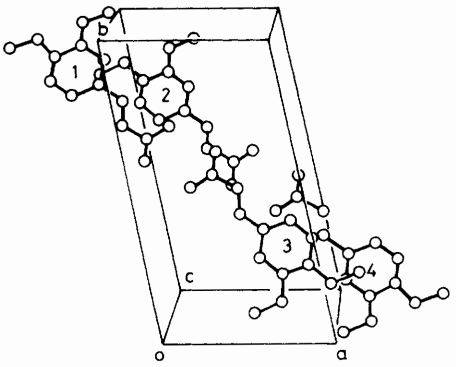


Figure 6. Drawing of the (2) crystal structure showing the four molecules in the unit cell. Molecule code: 2,4 x, $1 + y$, z; 1,3 $1 - x$, $2 - y$, $1 - z$

The distance between the double bonds in molecules 1 and 2 is 5.40 Å and is too long to permit topochemical photoreaction in the solid state. This orientation of molecules is reminiscent of the γ-packing for example in *p*-methoxycinnamic acid.[21]

Figure 7 shows shaded molecule 2 ($1 - x$, $-y$, $1 - z$), molecule 3 (x, $1 + y$, z), which is related to 2 by a centre of symmetry at ($\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$), and molecule 3^{i} (x, $1 + y$, $-1 + z$) which is obtained from molecule 3 by translation. Note that molecules 2 and 3^{i} are related by a centre of symmetry at ($\frac{1}{2}$, $\frac{1}{2}$, 0). The distance between the double bonds of molecules 2 and 3 is 6.80 Å and thus too great to permit solid-state photoreaction. However, the double bonds of molecules 2 and 3^{i} are only 4.04 Å apart. Clearly topochemical photodimerisation is permitted here and it is this intermolecular geometry that leads to the formation of dimer (6) when acid (2) is irradiated in the solid state. The corresponding molecules 1 and 4 are not potentially reactive, there being no near neighbours within photoreactive distance. That only half the molecules in the structure are potentially reactive is nicely confirmed by the *ca.* 40% yield of truxillic photodimer after prolonged irradiation in the solid state, the rest of the material being unreacted acid (2). All these intermolecular arrangements are summarised in Figure 8 which is a stereoview of the crystal structure showing the contents of two unit cells.

There are several features that the crystal structures of acid

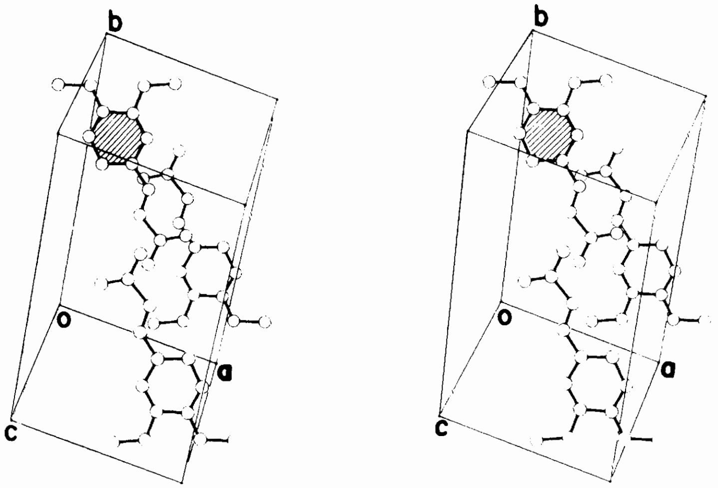


Figure 7. Stereodrawing of the (2) crystal structure showing molecules related by an inversion centre

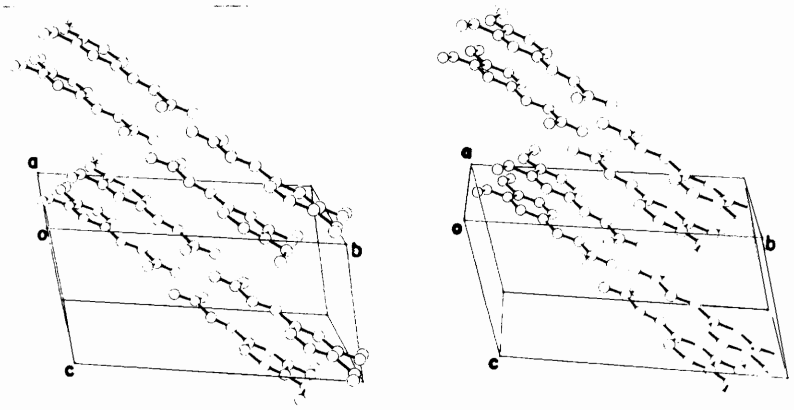


Figure 8. Stereodrawing of the (2) crystal structure showing the contents of two unit cells. Note that all the molecules are nearly parallel to (022)

(2) and complex (10) have in common.[26] The cell dimensions are very similar with two of the axial repeats being nearly equal in each case. Both space groups are $P\bar{1}$ and there are four acid molecules in both the unit cells. In the case of complex (10), a dimethoxycinnamic acid molecule is hydrogen bonded to a dinitrocinnamic acid molecule and this hydrogen-bonded dimer clearly cannot lie on an inversion centre. In the case of acid (2), the two hydrogen-bonded molecules are related by a pseudo-centre of symmetry. Thus in both cases, hydrogen-bonded molecules that form the dimer are symmetry independent while the centres of symmetry relate pairs of these dimers. It seems likely that the approximately equal sizes of the dinitro and the dimethoxy acid molecules would allow the complex to crystallise in a structure that bears a certain resemblance to the crystal structure of acid (2). However, there are also important differences in the two crystal structures. Notably, the two components of the complex participate in donor–acceptor interactions that are of course not possible in the structure of acid (2) itself.

The crystal structures of acid (2) and complex (10) highlight the fact that all *trans*-cinnamic acid structures need not necessarily conform rigorously to one of the types, α, β, or γ, on the basis of the lengths of their short axis as described by Schmidt.[6] Acid (2) crystallises in what is formally an α-structure since the short axis is greater than 5.1 Å. However, in addition to the centrosymmetric motif that is characteristic of the α-acids, there is a pseudo-γ type of stacking too. Complex (10) could also be classified as an α-structure since its short axis is greater than 5.1 Å. Here, however, potentially photoreactive molecules are not related by an inversion centre and the spacing of molecules is more reminiscent of the β- and γ-acids. In fact, the presence of two types of acid molecules in the crystal precludes a formal clarification as α, β or γ. It would certainly seem, then, that more complicated *trans*-cinnamic acid crystal structures, especially those where there are two or more molecules in the asymmetric unit, cannot be readily described in terms of Schmidt's criteria that have been so eminently successful for the simpler derivatives.[6] Clearly there is a need for more structural information in these cases.

Acknowledgements

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