

# Fluorine in crystal engineering: photodimerization of (1*E*,3*E*)-1-phenyl-4-pentafluorophenylbuta-1,3-dienes in the crystalline state

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(1*E*,3*E*)-1,4-Diphenylbuta-1,3-diene is photostable in the crystalline state, while fluoro-substitution induces reactivity. Crystals of (1*E*,3*E*)-1-pentafluorophenyl-4-(4-methoxyphenyl)buta-1,3-diene **1**, (1*E*,3*E*)-1-pentafluorophenyl-4-(4-methylphenyl)buta-1,3-diene **2** and (1*E*,3*E*)-1-pentafluorophenyl-4-phenylbuta-1,3-diene **3** undergo double [2+2] photodimerization topochemically to yield *anti* head-to-tail photodimers in the crystalline state. Remarkably fluoro-substitution brings the reactant molecules into an *anti* head-to-tail arrangement in the crystal lattice with weak intermolecular interactions: C–H ⋯ F, F ⋯ F, C–H ⋯ π, π ⋯ π.

## Introduction

It is well known that if potentially reactive double bonds are oriented parallel to each other and separated by approximately 4 Å, then [2+2] photodimerization takes place with a minimum of atomic and molecular motion.<sup>1</sup> In general, the environment of the olefinic double bonds in these crystals conforms to one of the three principal types of  $\alpha$ ,  $\beta$  or  $\gamma$ . Extensive studies on chloro,<sup>2</sup> bromo,<sup>3</sup> methoxy<sup>4</sup> and acetoxy<sup>5</sup> derivatives of coumarin and cinnamic acid have led to the understanding of the packing modes of the monomeric molecular units in relation to the substituent pattern. Recent studies on fluoro-substituted 4-styrylcoumarins<sup>6</sup> and coumarins<sup>7</sup> indicate a preference for the  $\beta$ -packing modes and the presence of fluorine appears to serve as a steering agent.

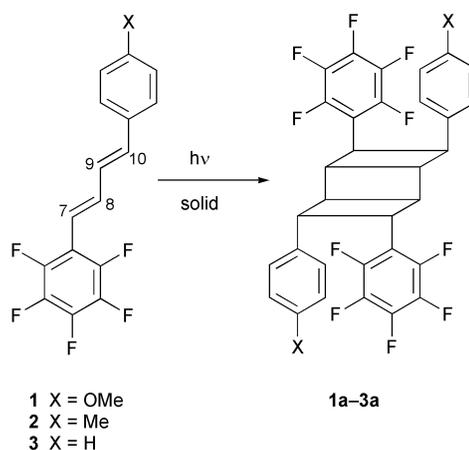
In 4-styrylcoumarin,<sup>8</sup> there are two reactive double bonds, e.g., the pyrone and the styrenic bond. Both, in principle, could undergo photodimerization. However, out of the 16 photo-reactive 4-styrylcoumarin derivatives investigated so far for their solid state photobehaviour, only one reacts across the pyrone double bond.<sup>8</sup> None of the 4-styrylcoumarin and ( $\pm$ )-benzylidenepiperitone derivatives undergoes double [2+2] photodimerization in the crystalline state.<sup>9</sup> Recently Hopf *et al.* reported multiple [2+2] topochemical photodimerization reactions both in solution as well as in the solid state.<sup>10</sup> It is known that crystals of 1,4-dicinnamoylbenzene undergo double [2+2] photodimerization topochemically to yield a cyclic product.<sup>11</sup> To gain further insight into the steering ability of fluorine in engineering crystals, it was considered worthwhile to examine the effect of fluoro-substituted (1*E*,3*E*)-buta-1,3-dienes on molecular packing and their photobehaviour. In this article, we discuss the results for fluoro-substituted (1*E*,3*E*)-1-pentafluorophenyl-4-(4-methoxyphenyl)buta-1,3-diene **1**, (1*E*,3*E*)-1-pentafluorophenyl-4-(4-methylphenyl)buta-1,3-diene **2** and (1*E*,3*E*)-1-pentafluorophenyl-4-phenylbuta-1,3-diene **3**.

## Results and discussion

Compounds **1**, **2** and **3** were synthesised and purified by the procedure described in the literature.<sup>12</sup> Crystals were grown

from a 1 : 3 mixture of chloroform and ethanol. The powder samples of **1–3** were irradiated simultaneously in a Rayonet photochemical reactor ( $\lambda_{\max} = 320 \pm 20$  nm) for *ca.* 24 h at room temperature. During irradiation care was taken to expose samples uniformly by shaking the containers at regular intervals. Irradiation was continued until there was no further increase in product formation. The progress of the reaction was monitored by thin layer chromatography and <sup>1</sup>H NMR spectroscopy. The photodimers **1a**, **2a** and **3a** were separated from their corresponding monomers (**1**, **2** and **3**) by column chromatography, eluting with petroleum ether.

The molecular ion peaks at *m/z* 652, 620 and 592 in the mass spectra indicated the formation of the photodimers **1a**, **2a** and **3a**, respectively (Scheme 1). This was further confirmed by <sup>1</sup>H



Scheme 1

NMR (disappearance of the olefinic protons of the monomers and the appearance of peaks at around  $\delta$  3.5–4.5 for the photodimers corresponding to cyclobutyl protons). The yields of photoproducts in all the cases were *ca.* 23–25% as determined from the <sup>1</sup>H NMR spectra.

Compounds **1–3** with two potentially reactive double bonds [C(7)=C(8)] and [C(9)=C(10)] may, in principle, undergo either a single or a double [2+2] photodimerization in the solid state, depending on the topochemistry. The photodimers, in principle, can adopt any one of the four configurations: *syn*-HH, *syn*-HT, *anti*-HH and *anti*-HT (HH = head-to-head; HT = head-to-tail).

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Irradiation of compounds **1–3** in the crystalline state leads to formation of the centrosymmetric *anti*-HT photodimers (**1a–3a**) across both the double bonds [C(7)=C(8)] and [C(9)=C(10)]. The lower yields of photoproducts *ca.* 23–25% in all the cases is due to the fact that the [2+2] photodimerization reaction occurs in a stepwise fashion.‡ The *anti*-HT stereochemistry of the photodimers **1a–3a** was confirmed on the basis of the arrangement of molecules in the crystalline state (Figs. 1, 2 and 3).

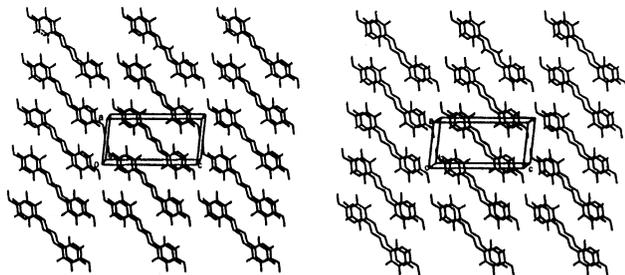


Fig. 1 A perspective view of the crystal packing of **1**.

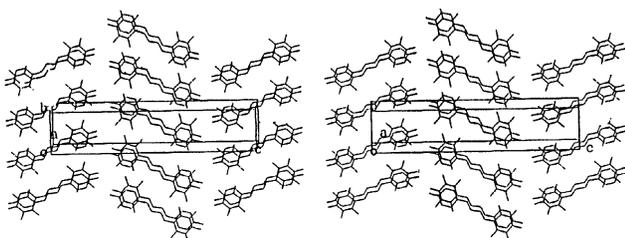


Fig. 2 A perspective view of the crystal packing of **2**.

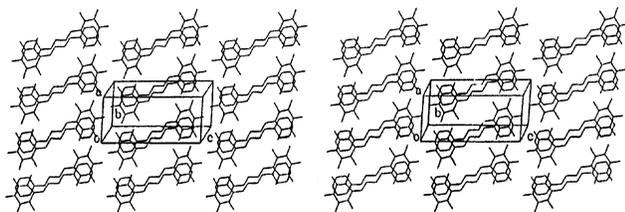


Fig. 3 A perspective view of the crystal packing of **3**.

### Structure–reactivity correlations

To achieve [2+2] topochemical photodimerization reactions in the crystalline state, the centre-to-centre distance between the reactive double bonds should be less than *ca.* 4.2 Å, and the best overlap of the  $\pi$ -orbitals of the reactive partners can be identified through the geometrical parameters  $\theta_1$ ,  $\theta_2$ ,  $\theta_3$  and  $d$ .<sup>1,4</sup> The ideal values of these parameters are 0, 90, 90° and 0 Å.<sup>4</sup> The centre-to-centre distance between the centrosymmetrically related reactive double bonds [C(7)=C(8)] and [C(9)=C(10)] is 3.852 and 3.844 Å in crystal **1**, 3.799 and 3.745 Å in crystal **2** and 3.724 and 3.895 Å in crystal **3**. The calculated values of  $\theta_1$ ,  $\theta_2$ ,  $\theta_3$  and  $d$  for the double bonds C(7)=C(8) and C(9)=C(10) of crystal **1** are 0.0, 105.1, 78.7° and 0.63 Å and 0.0, 83.2, 110.9° and 1.25 Å, respectively. In crystal **2** these values are 0.0, 66.4, 85.1° and 0.29 Å for C(7)=C(8) and 0.0, 117.1, 97.7° and 0.44 Å for C(9)=C(10) and those for crystal **3** are 0.0, 116.8, 99.9° and 0.42 Å for C(7)=C(8) and 0.0, 78.9, 99.4° and 0.58 Å for C(9)=C(10). Although these values differ from the ideal values, the dimerization takes place across the reactive double

‡ NMR spectra were recorded at different stages of the photoreaction. After photolysis for about 12–14 h, <sup>1</sup>H NMR showed the presence of two peaks at around  $\delta$  3.5–4.5, which corresponds to one cyclobutane. The <sup>1</sup>H NMR of the reaction mixture after about 24 h of photolysis showed the formation of the double [2+2] photocycloaddition product. Photolysis was continued until there was no further progress in the dimer formation.

bonds, which is confirmed by thin layer chromatography, and the <sup>1</sup>H NMR and mass spectra. In fact, in most cases, it has been observed that the values for  $\theta_1$ ,  $\theta_2$ ,  $\theta_3$  and  $d$  do not correspond to the ideal values.<sup>13</sup> This finding is attributed to the orientational flexibility of the reactants in the reaction cavity.

### Analysis of short intermolecular interactions

From analysis of the intermolecular distances, it is found that there are a few short intermolecular interactions (such as C–H  $\cdots$  O, C–F  $\cdots$  H–C and F–F) that are smaller than the sum of van der Waals radii. The relevant geometrical parameters are summarised in Table 1. The van der Waals radii<sup>14</sup> used were C = 1.75, H = 1.20 and F = 1.47 Å and only those with C–H  $\cdots$  F angles greater than 110° were considered. The intermolecular contacts in Table 1 clearly indicate that possibly only in crystal **1** are there two significant but weak F  $\cdots$  F interactions. Based on the Cambridge Structural Database (CSD), the question of the presence or absence of C–H  $\cdots$  F interaction has been discussed at length by different investigators.<sup>15</sup> Shimoni and Glusker<sup>16</sup> concluded that C–F  $\cdots$  H–X (X = C, N, O) interactions are much weaker than C=O  $\cdots$  H–X (X = C, N, O), but their role in the prediction of molecular packing in crystals cannot be overlooked. Howard *et al.*<sup>17</sup> concluded that C–H  $\cdots$  F contacts have very little significance in terms of energy. Recently, Taylor and Dunitz<sup>18</sup> carried out a statistical analysis of the Cambridge Structural Database and the Brookhaven Protein Data Bank and concluded that fluorine rarely acts as a hydrogen bond acceptor.

### Conclusions

From analysis of the crystal packing, we believe that the substitution of fluorine in place of hydrogen brings about significant changes in the packing modes in the lattice. The molecules in all three structures pack in an *anti*-HT fashion and are at distances suitable for double [2+2] photodimerization. In *anti*-HT packing, the attractive coulombic interactions between the phenyl group of one molecule and its fluoro-substituted phenyl group would be expected to add to the overall stability of these crystals. It is noteworthy that for all the crystals the yields are low (*ca.* 23–25%). This may be attributed to a possible stepwise mechanism for the reaction in the crystals, although it could be partly due to the breakdown of the crystal to an amorphous material. There are a very few short (based on the assumed van der Waals radii) interactions in these structures in concurrence with the observations from the detailed data base analysis carried out by Howard,<sup>17</sup> and Dunitz.<sup>18</sup>

### Experimental

Compounds **1**, **2** and **3** were synthesised and purified by the procedure described in the literature.<sup>12</sup> *n*-Butyllithium (2 mmol) was added to a stirred suspension of allyltriphenylphosphonium bromide (2 mmol) and THF (10 ml) at –78 °C under nitrogen. After stirring at 0 °C for 0.5 h, the corresponding ylide was formed. Without isolation, hexafluorobenzene (1 mmol) was added slowly and the reaction mixture stirred at 20 °C for about 24–30 h. Aldehyde (1.1 mmol) was added and the mixture stirred at 20 °C for about 24–30 h. Diethyl ether (30 ml) was then added and the organic layer was washed with water and dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. Evaporation of the solvent gave a residue that was purified by column chromatography on silica gel, eluting with light petroleum ether, recrystallized from ethanol. The <sup>1</sup>H NMR coupling constants confirmed that (1*E*,3*E*)- and (1*E*,3*Z*)-isomers are formed in a ratio of ~3 : 1 for compounds **1**, **2** and **3**. Repeated crystallization from chloroform and ethanol (1 : 3 ratio) selectively yielded the needle-shaped, colourless (1*E*,3*E*)-isomer.

**Table 1** Geometrical parameters of both C–H ... O and C–H ... F contacts<sup>a</sup>

	O ... H or F ... H/Å	C–H ... O or C–H ... F/°	C ... F or C ... O/Å
Crystal 1			
O(1) <sup>a</sup> ... H(C15) <sup>f</sup>	2.70	155.1	3.57
F(1) ... H(C13) <sup>h</sup>	2.51	134.3	3.23
F(4) <sup>b</sup> ... H(C16) <sup>f</sup>	2.62	147.8	3.44
F(2) <sup>c</sup> ... HB(C17)	2.64	111.2	3.11
	F ... F		
F(4) <sup>d</sup> ... F(1)	2.91		
F(2) ... F(3) <sup>i</sup>	2.85		
Crystal 2			
F(4) <sup>e</sup> ... H(C12) <sup>f</sup>	2.64	128.5	3.29
F(1) ... H(C15) <sup>k</sup>	2.59	125.9	3.22
Crystal 3			
F(1) <sup>f</sup> ... H(C12)	2.65	130.9	3.34
F(4) <sup>g</sup> ... H(C16) <sup>a</sup>	2.56	136.7	3.29

Symmetry transformations used to obtain equivalent atoms: <sup>a</sup>(2 - x, y, z); <sup>b</sup>(1 + x, y, z); <sup>c</sup>(1 + x, y, 1 + z); <sup>d</sup>(1 + x, y, z); <sup>e</sup>(x, 1 + y, z); <sup>f</sup>(1 - x, 1 - y, 1 - z); <sup>g</sup>(-x, -y, 1 - z); <sup>h</sup>(2 - x, 2 - y, 1 - z); <sup>i</sup>(-x, 2 - y, -z); <sup>j</sup>(1 - x, -y, -z); <sup>k</sup>(-x, 1 - y, -z).

### Irradiation procedure

The finely powdered crystalline samples of **1**, **2** and **3**, placed at a distance of ca. 30 cm from the Rayonet lamps ( $\lambda_{\max}$  300 ± 20 nm), were irradiated simultaneously for about 24 h. During irradiation care was taken to expose samples uniformly by shaking the containers at regular intervals. A uniform temperature in the irradiation chamber was ensured by keeping a cooling fan on during irradiation. Irradiation was continued until there was no further increase in product formation. The progress of the reaction was monitored by <sup>1</sup>H NMR. Photodimers **1a–3a** were purified by column chromatography over silica gel using light petroleum ether as eluant.

### Crystal structure determination of compounds **1**, **2** and **3** §

Single crystals of compounds **1–3** were obtained from chloroform and ethanol (1 : 3 ratio). Three-dimensional intensity data were collected on an Enraf-Nonius CAD4 diffractometer using graphite monochromated Mo-K $\alpha$  radiation at 293 K, in  $\omega$ -2 $\theta$  mode. The structures were solved using direct methods (SHELXS-86) and refined using SHELXL-93.

**Crystal 1.** C<sub>17</sub>H<sub>11</sub>F<sub>5</sub>O, *M* = 326.26, triclinic, *a* = 6.654(4), *b* = 7.666(9), *c* = 13.649(5) Å,  $\alpha$  = 90.29(6),  $\beta$  = 95.59(3),  $\gamma$  = 97.95(5)°, *V* = 686.1(9) Å<sup>3</sup>, space group *P* $\bar{1}$ , *Z* = 2, *R* = 0.055.

**Crystal 2.** C<sub>17</sub>H<sub>11</sub>F<sub>5</sub>, *M* = 310.26, monoclinic, *a* = 7.541(6), *b* = 5.890(4), *c* = 30.725(9) Å,  $\beta$  = 90.11°, *V* = 1365.0(2) Å<sup>3</sup>, space group *P*2<sub>1</sub>/*n*, *Z* = 4, *R* = 0.061.

**Crystal 3.** C<sub>16</sub>H<sub>9</sub>F<sub>5</sub>, *M* = 296.23, triclinic, *a* = 6.085(1), *b* = 7.497(2), *c* = 14.459(4) Å,  $\alpha$  = 98.56(2),  $\beta$  = 94.48(2),  $\gamma$  = 92.95(2)°, *V* = 648.9(3) Å<sup>3</sup>, space group *P* $\bar{1}$ , *Z* = 2, *R* = 0.045.

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§ The crystal structures of **1**, **2** and **3** are to be published elsewhere.

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