Mapping the Molecular Pathway during Photoaddition of Guest Acetophenone and *p*-Fluoroacetophenone to Host Deoxycholic Acid as Studied by X-ray Diffraction in Systems Undergoing Single-Crystal-to-Single-Crystal Transformation

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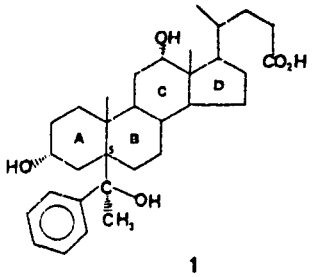
Abstract: The structures of the partially reacted crystals of the two complexes (5:2) deoxycholic acid (DCA)–acetophenone and (8:3) DCA–*p*-fluoroacetophenone were determined by low-temperature (−170 °C) X-ray diffraction. The structure analyses indicated that both independent guest acetophenone molecules G′ and G in DCA–acetophenone react and that in DCA–*p*-fluoroacetophenone the guest molecule G′ reacts whereas the other guest molecule G remains unreacted because of packing of G and G′ molecules along the channel. The observed guest photoconversion in DCA–acetophenone is 40%; the maximum value according to packing considerations is 50%. In DCA–*p*-fluoroacetophenone the observed guest photoconversion is 35%, very close to the maximum theoretical yield of 33% based on packing considerations. The analysis demonstrated that during the course of photoconversion there is minimal motion of the (guest) phenyl ring, pronounced rotation of the acetyl group about the exocyclic C–C bond, and displacement of unreacted and reacted molecules. Atom–atom potential energy calculations showed that in DCA–acetophenone a guest ketyl radical with a pyramidal geometry may rotate by a full 180° without inducing prohibitively short intermolecular contacts.

1. Introduction

In a preceding paper[1] we examined the crystal structure of the channel inclusion complex (5:2) deoxycholic acid (labeled DCA)–acetophenone which yields a single diastereomeric photoaddition product **1**; the newly generated chiral carbon has an



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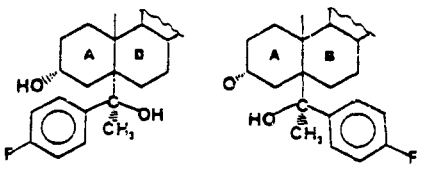
absolute configuration *S*, opposite to that expected from the host–guest packing at the reaction site, as depicted Scheme I. There are two independent acetophenone guest molecules G and G′ in the channel. Molecules G′ and G each makes contact with its neighboring potentially reactive steroid C5–H5 bond with almost the same geometry.

The crystal structure of the molecular complex (8:3) DCA–*p*-fluoroacetophenone[2] also yielded a single diastereomeric photoproduct, **2**, akin to **1**. However, the host–guest arrangement of this complex, depicted in Chart I, which contains two independent *p*-fluoroacetophenone guest molecules G and G′, suggested that photoirradiation should yield both the diastereomeric photoproducts **2** and **3**. Reaction between guest G′ and the steroid should yield **2** as in Scheme I, and reaction between guest G and the steroid should yield **3**.



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(1) Tang, C. P.; Chang, C. H.; Popovitz-Biro, R.; Frolow, F.; Lahav, M.; Leiserowitz, L.; McMullan, R. K. *J. Am. Chem. Soc.* **1985**, *107*, 4058.
(2) Weisinger-Lewin, Y.; Vaida, M.; Popovitz-Biro, R.; Chang, H. C.; Manning, D.; Frolow, F.; Lahav, M.; Leiserowiz, L. *Tetrahedron* (special issue), in press.

Scheme I

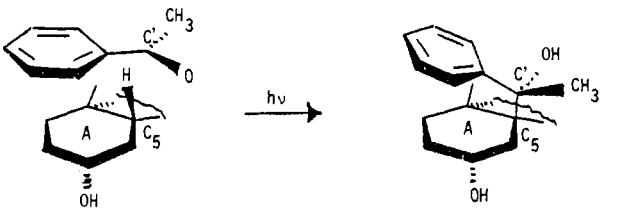
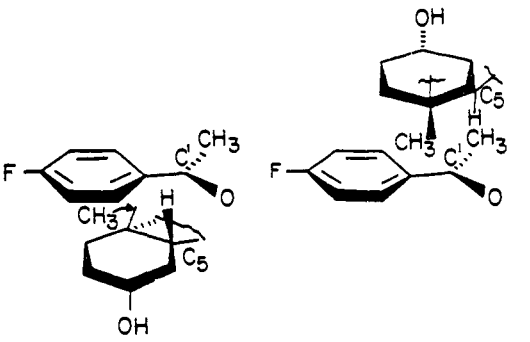


Chart I



In order to monitor the reaction pathway in DCA–acetophenone, which involves a net rotation of 180° of the guest acetyl group before photoaddition, and to explain the stereospecificity of the photoreaction in DCA–*p*-fluoroacetophenone we exploited the property that these crystalline complexes preserve their integrity on photoreaction. Thus we undertook a determination of the crystal structures of these two complexes after partial photoconversion. The structures of the unreacted complexes had been determined by low-temperature (−170 °C) X-ray diffraction in order to locate the guest molecules.[1,2] The reacted crystals also necessitated a low-temperature study in order to facilitate location of the various and disordered molecular species, host, guest, and photoproduct in the solid solution.

2. Results and Discussion

2.1. Required Time for Photoconversion of Single Crystal. We had to make certain that the UV-irradiated crystals had undergone sufficient photoconversion prior to measurement of their X-ray intensities and subsequent elucidation of their structures. Thus

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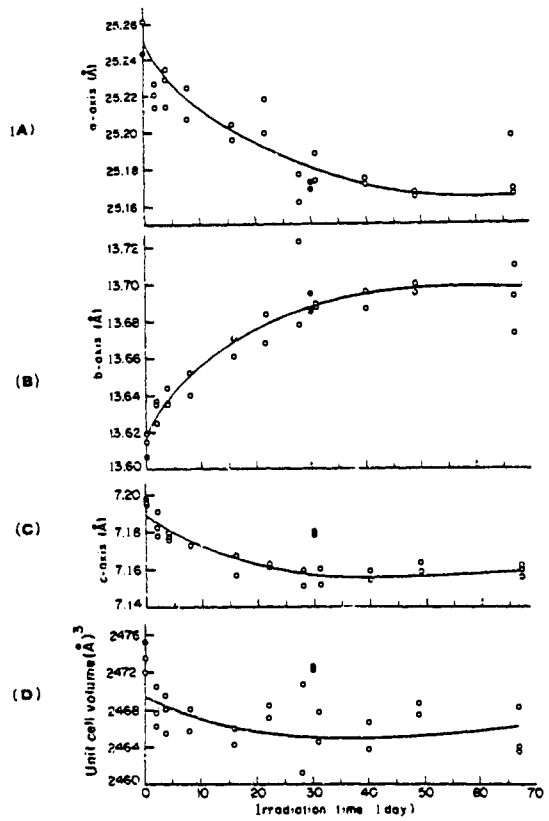


Figure 1. Changes in the lengths of axes a, b, c, and unit cell volume v of DCA–acetophenone shown in (A), (B), (C), and (D), respectively. The measurements were made on 24 crystals irradiated with UV light for different times up to 67 days.

we exposed 24 single crystals of DCA–acetophenone to UV light in various batches for different radiation times up to 67 days. The cell dimensions of each crystal were measured on a CAD-4 diffractometer at −170 °C. The crystals maintained their integrity and retained their space group symmetry. The changes in axial length Δa, Δb, and Δc and in unit cell volume Δv are given in Figure 1. Δa and Δb show an asymptotic trend with maximum values of 0.08 Å. We estimated from these curves that 30 days of UV irradiation would yield close to maximum photoconversion. Thus we exposed a single crystal of DCA–acetophenone and of DCA–*p*-fluoroacetophenone each to 30 days of UV light, by using the original crystals on which the X-ray diffraction data of the pure complexes had been measured.

The cell dimensions of these two crystals at −170 °C changed distinctly after UV irradiation (see section 3.1, Table I): for DCA–acetophenone, $\Delta a = -0.07$, $\Delta b = 0.08$, and $\Delta c = -0.02$ Å, almost as large as the maximum asymptotic changes (Figure 1). For DCA–*p*-fluoroacetophenone there is a similar trend: $\Delta a = -0.12$, $\Delta b = 0.10$, and $\Delta c = 0.06$ Å. X-ray diffraction data were collected on these two UV-irradiated crystals at −170 °C (see section 3.1 for details).

2.2. Structure and Reactivity of the UV-Irradiated Crystal of DCA–Acetophenone. The arrangement of the two independent guest molecules G and G′ in the channel of the unreacted crystal[1] is depicted in Figures 2 and 3. $G(x, y, z)$ and $G'(x, y, +z')$ are arranged in close-packed pairs separated by 8 Å which is equal to the c translation axis of 7.2 + 0.8 Å.

According to the structure-factor least-squares refinement (see section 3.1) the UV-irradiated crystal contains DCA, guest, and photoproduct **1**. The molecular overlap between these three components is displayed in Figure 4. According to the least-squares analysis both G and G′ had reacted, with individual yields of 0.50 and 0.34, respectively, resulting in an overall guest photoconversion of 0.42. The photoconversion was also derived independently from the refined occupancy of the photoproduct **1**, equivalent to 0.154, corresponding to a guest photoyield of 0.15/0.40 = 0.38, 0.4 being the guest–host molar ratio in the unreacted crystal. Taking the mean yields a guest photoconversion of 40%.

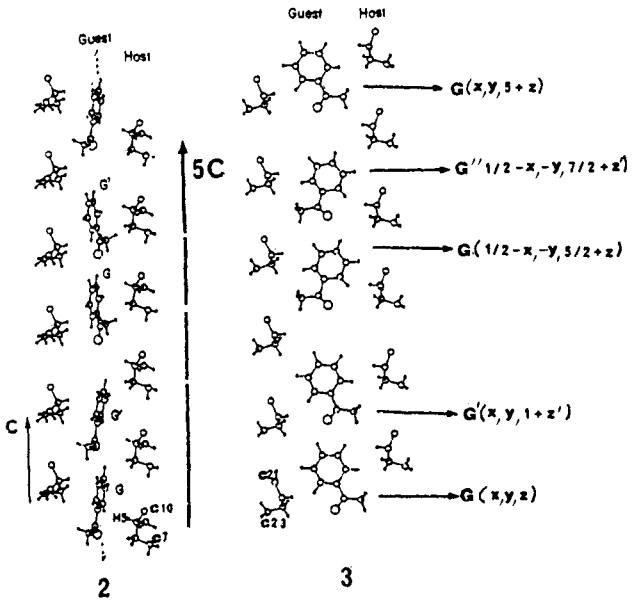


Figure 2. Close-packed arrangement of acetophenone molecules in a channel derived from the two independent molecules $G(x, y, z)$ and $G'(x, y, 1 + z')$. (The coordinates of the channel 2 axis are $x = {}^1/_4$, $y = 0$). View edge-on to plane of guest molecules. The channel walls shown are a part of steroid rings A and B.

Figure 3. Same as Figure 2—view perpendicular to plane of guest molecules. The channel walls are part of the steroid side chain.

According to the least-squares refinement, an unreacted guest molecule cannot occupy its original site if its close-packed neighbor has reacted; the interatomic O···C or C···C contact induced between the unreacted guest (G or G′) and its reacted neighbor (G′ or G, respectively) would be in the range 2.8–2.9 Å, too short by about 0.3 Å. In subsequent refinement of the reacted crystal, G was replaced by two sites, Gα and Gβ and G′ by G′α and G′β. Gα and G′α are the unreacted close-packed pair (Figure 5a) separated by the same distance as the G, G′ pair in the unreacted crystal. If a G′ molecule reacts, as shown in Figure 5b, its original nearest neighbor G will as a result move away from its reacted neighbor to reach a new location, specified by Gβ to permit reasonable contacts. These relocations are made possible by the large separation between neighboring G and G′ molecules not belonging to a close-packed pair (see Figures 2 and 3). The analogous situation also arises if G reacts so inducing G′ to move to a new location specified by G′β (Figure 5c). Consequently, intermolecular contacts permit either G or G′ of a close-packed pair to react, leaving as its neighbor G′β or Gβ, respectively. The relative positions of Gα, G′α, Gβ, G′β, DCA, and photoproduct **1** are shown in Figure 6.

The molecular packing in the channel precludes reaction of both G and G′ molecules of a close-packed pair, because in the resulting arrangement the two reacted molecules would be related by c translation and thus incorporate too close an intermolecular distance of 2.2 Å between C atoms of the reacted G′ and G molecules, respectively (see Figure 7). Such a constraint on the reactivity of guest molecules does not apply to neighboring G and G′ molecules which belong to adjacent close-packed pairs (Figures 2 and 3); the gap between these two molecules [i.e., $G(x, y, z)$ and $G'({}^1/_2 - x, -y, -{}^3/_2 + z')$] is sufficiently large to permit either G or G′ to react. As mentioned above intermolecular contacts permit either G or G′ of a close-packed pair to react but not both (Figure 7). Therefore 50% would appear to be the maximum achievable guest photoconversion. This conclusion is compatible with the observed changes in cell axes a, b, and c as a function of UV irradiation time (Figure 1). The 30-day time span of UV irradiation yielded a guest photoconversion of 40%. It also induced, relative to the unreacted crystal, changes in the lengths of axes a and b (Δc may be neglected, being relatively small) as high as

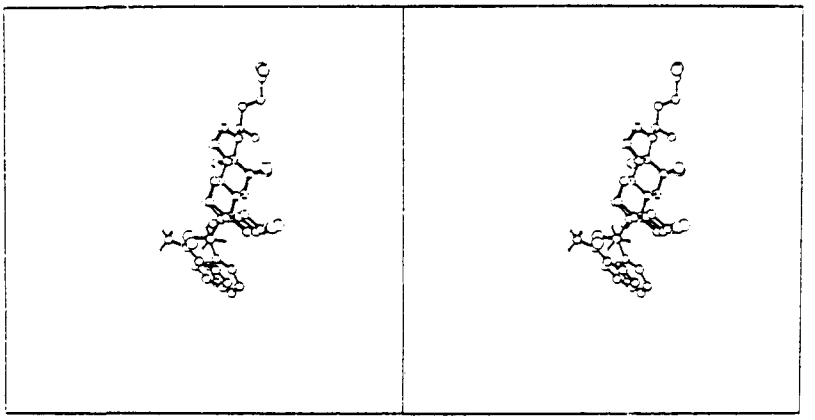


Figure 4. Stereoscopic view along the channel axis of solid solution comprising overlapping DCA steroid, photoproduct **1**, and guest acetophenone at a molecular site. (H atoms of the steroid backbone have not been inserted).

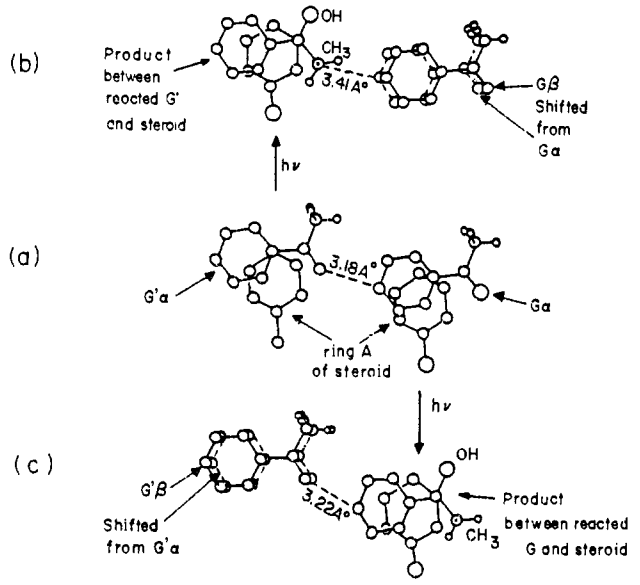


Figure 5. (a) Close-packed pair of $G\alpha$ and $G'\alpha$ molecules. Rings A of DCA related by c axis also shown. (b) Close-packed pair in which G' reacted. Its neighbor $G\beta$ shifted along $-c$ with respect to $G\alpha$ to accommodate acceptable intermolecular distance of 3.4 Å. (c) Pair in which G reacted. Its neighbor $G'\beta$ shifted along $+c$ with respect to $G'\alpha$ to accommodate acceptable intermolecular distance of 3.2 Å.

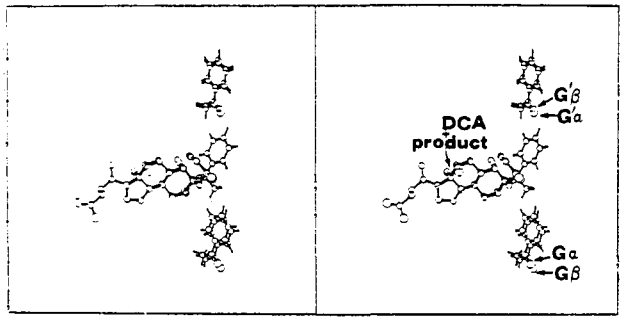


Figure 6. Stereoscopic view showing geometric relationship between overlapping unreacted DCA, photoproduct **1**, and the position of the neighboring guest molecules. $G\alpha$ and $G'\alpha$ depict the positions of unreacted guest prior to reaction of a neighboring guest. $G\beta$ and $G'\beta$ are the corresponding positions after reaction of a neighboring guest.

83% of their asymptotic changes after 67 days of UV irradiation. Associating the asymptotic values of a and b with maximum photoconversion we may suppose that 40% photoconversion after 30 days irradiation is close to the maximum yield. This deduction supports the independent conclusion that 50% is the maximum guest photoconversion.

2.3. Structure and Reactivity of the UV-Irradiated Crystal of DCA-*p*-Fluoroacetophenone. In the unreacted crystal of DCA-*p*-fluoroacetophenone[2] the guest–host molar ratio (or guest occupancy) is 3:8 = 0.375. The guest molecules G and G' are arranged along the channel in close-packed triplets G'GG' (Figure 8). The guest occupancies of G' and G were actually found to be equal to 0.258 (4) and 0.113 (4), respectively, with a total of 0.371 (6). Packing considerations[2] indicated that the occupancy of G' is maximally 1:4. Owing to the high molecular overlap between G and G' in the channel there was a high correlation

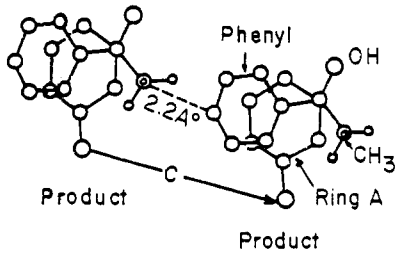


Figure 7. G and G' of a close-packed pair have both reacted to yield a pair of photoproducts **1** related by c translation with a prohibitively short intermolecular distance. Only ring A and newly generated moiety $C(OH)(CH_3)C_6H_5$ are shown. View is along the $C[OHCH_3C_6H_5]$–C5 bond.

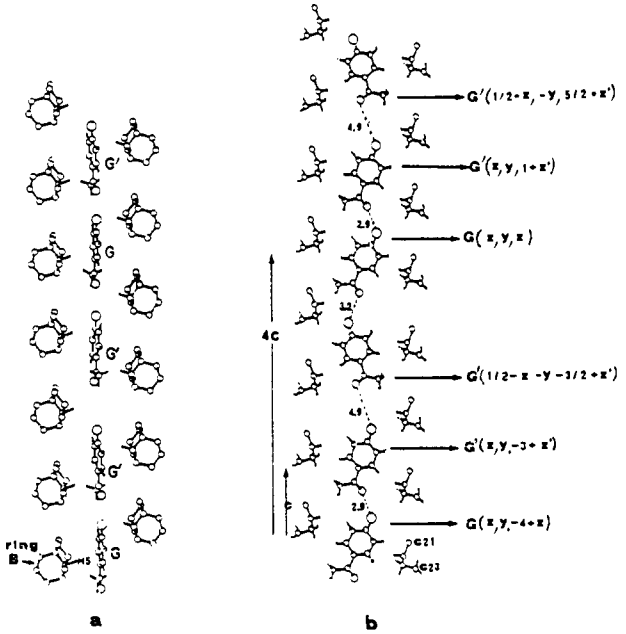


Figure 8. Unreacted DCA-*p*-fluoroacetophenone. Packing of guest molecules in the channel whose walls are formed by the host DCA molecules: (a) edge-on to plane of guest molecules and (b) perpendicular to plane of guest molecules. The guest molecules are arranged in a superstructure along the channel comprising close-packed triplets: $G'(x, y, 1 + z')$, $G(x, y, z)$, and $G'(^1/_2 - x, -y, -^3/_2 + z')$. These triplets are arranged by a translation of $4C$ as depicted.

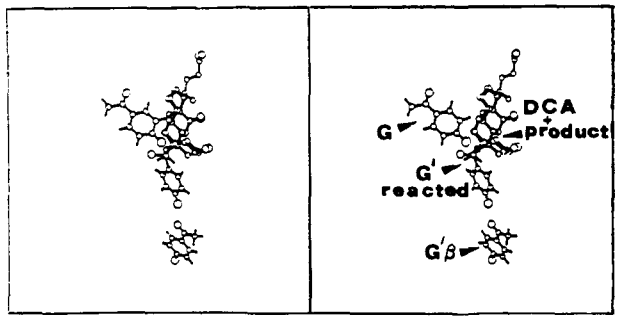


Figure 9. Stereoscopic view of solid solution containing unreacted DCA, photoproduct **2**, *p*-fluoroacetophenone guests G and G'.

between the refined occupancies of G and G' in the structure-factor least-squares analysis. Thus it is perfectly reasonable to take the occupancy of G to be 0.25 and to set the occupancy of G' = 0.371 (6) − 0.250 (4) = 0.121 (7).

Part of the solid solution of UV-irradiated DCA–*p*-fluoroacetophenone comprising DCA, photoproduct **2**, and G and G' is shown in Figure 9. According to the least-squares refinement (see section 3.3) the occupancies of unreacted DCA, the reacted DCA photoproduct **2**, and the unreacted guests G' and G are 0.870 (8), 0.130 (8), 0.118 (5), and 0.107 (5), respectively. Thus the occupancy of the unreacted G' molecule is reduced from 0.250 (4) to 0.118 (5) = 0.132 (6) on irradiation. The fraction of G' molecules that reacted equals 0.132 (6)/0.250 (4) = 0.53 (3). The occupancy of unreacted G is reduced from 0.121 (7) to 0.107 (5) = 0.014 (9), corresponding to the fraction 0.014 (9)/0.121 (7) = 0.12 (5) of G molecules that reacted. The overall reduction in guest occupancy is 0.371 (6) − [0.118 (5) + 0.107 (4)] = 0.146 (9) of which the fraction 0.90 [=0.132/0.146] are G' molecules and 0.10 [=0.014/0.146] are G molecules. This total reduction in guest occupancy of 0.146 (9) is almost balanced by the independently refined occupancy of 0.130 (8) of the reacted steroid molecule **2**; indeed the latter value is exactly balanced by the reduction of 0.132 (6) in occupancy of G'. These least-squares results indicate that photoconversion arises overwhelmingly, if not completely, from reaction between G' and steroid; the minimum molar fraction of reacted host molecules involving guest G' = 0.132/0.146 = 0.9.

It is still necessary to understand this difference in reactivity of G and G' on topochemical grounds. For this purpose let us consider the four possible ways (a–d) in which the nearest neighbor reacted and unreacted guest molecules may pack in the channel of the irradiated complex: First we note that the two G' molecules of the close-packed triplet G'G G' in the unreacted crystal (Figure 8) have different guest environments arising from the superstructure in the channel. Thus we label them G'α and G'β as shown in Figure 10a.

(a) Let us assume that only one of the two fluoroacetophenone molecules G' of triplet G'αGG'β (Figure 10a) reacts, say G'α; the resulting photoaddition product molecule will be flanked by guest molecules G and G'β (Figure 10b). The shortest contact in the channel between this product and the guest G would be 3.0 Å between C30 (product) and F(G), which is about 0.2 Å less than the normal van der Waals distance.[3] The other flanking molecule, G'β, is sufficiently far removed from reacted G'α so as not to preclude reaction. Thus it is borderline whether G'α may react without incurring short contacts.

(b) Now assume that the other *p*-fluoroacetophenone molecule, G'β, has reacted in the channel. The product molecule will now be flanked by guest molecules G and G'α (Figure 10c). The shortest contact between the product and the guest G would be 3.2 Å, between O(G) and F(product), which is reasonable. The product is also sufficiently displaced from adjacent molecule G'α. Thus intermolecular contacts should allow G'β to react.

(c) We now consider the intermolecular contacts encountered were G to react. According to the host–guest arrangement in the unreacted crystal (Figure 11a) molecule G exposes acetyl face re to a C5–H5 bond of host steroid labeled S1 and face si to the

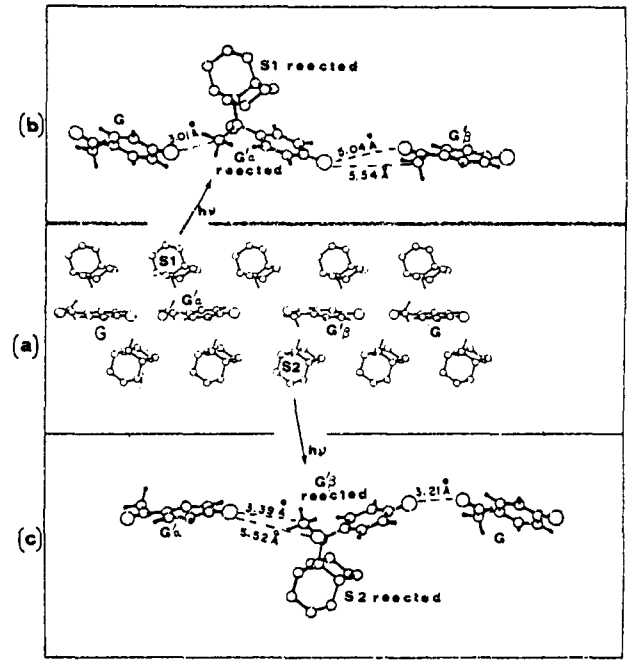


Figure 10. (a) Part of the chain of fluoroacetophenone guest molecules sandwiched between rings A and B of the host DCA molecules in the unreacted crystal. The to-be-abstracted H5 atom attached to C5 of DCA is the only steroid H atom drawn. (b) Contacts between reacted G'α, bonded to steroid S1 and neighboring G and G'β molecules. (c) Contacts between reacted G'β, bonded to steroid S2 and neighboring G' and G molecules.

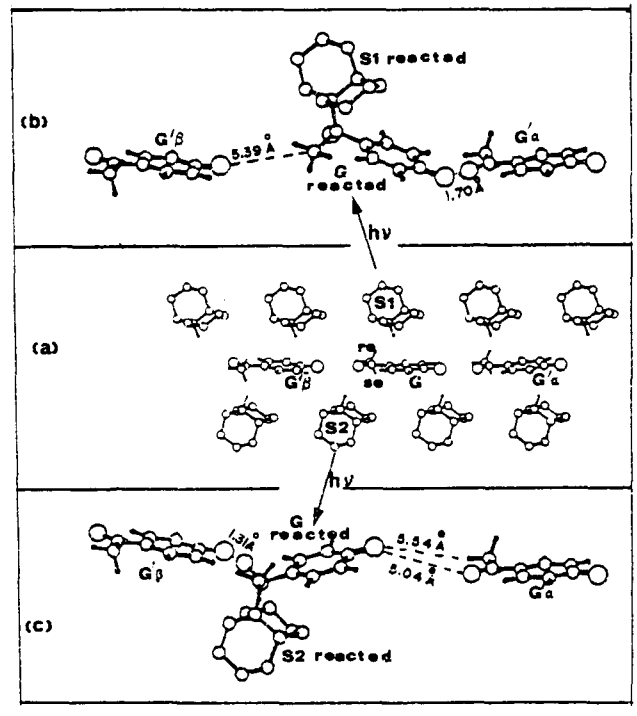


Figure 11. (a) Fluoroacetophenone guest triplet G'β–G–G'α sandwiched between rings A and B of the host DCA molecules in the unreacted crystal. The prochiral *si* and *re* sides of guest G are denoted. (b) Hypothetical arrangements were steroid S1 and guest G to react across guest face *re* to yield product flanked by G'β and G'α. (c) Hypothetical arrangements were steroid S2 and guest G to react across guest face *si* to yield product flanked by G'β and G'α.

C5–H5 bond of host steroid S2. In contrast, G' exposes only face re to the C5–H5 bond. In terms of host–guest distances[2] the si face of G is in a more advantageous position for reaction than face re (H5···O = 2.6 and 3.7 Å, respectively). Nevertheless we shall consider both possibilities as shown in Figure 11 where G is flanked by G'β and G'α. Were G to react with steroid S1, the

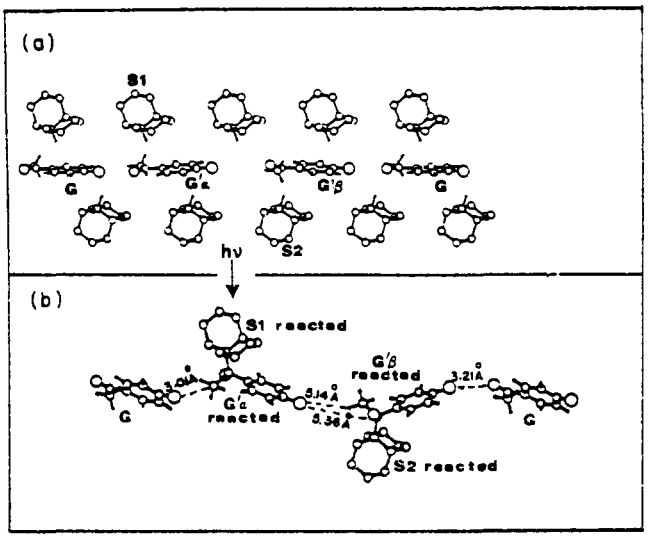


Figure 12. (a) Chain of fluoroacetophenone guest molecules sandwiched between rings A and B of the host DCA molecules in the unreacted crystal. (b) Arrangement in which G'α has reacted with steroid S1 and G'β with steroid S2.

photoproduct would make too close a contact with G'α, because of the resulting 1.7-Å separation between an F atom of the product and O of G' (Figure 11c). Were G to react with steroid S2, this would lead to a distance of 1.3-Å between O (product) and the F atom of G'β (Figure 11b). These intermolecular distances are prohibitive. We may also dismiss the remaining possibility in which reacted G is flanked on one side by an already reacted G'β molecule. This would yield two photoproducts related by *c*-translation resulting in prohibitively short contacts in the channel as already pointed out for DCA–acetophenone (Figure 7).

(d) Here we envisage that two neighbors, G'α and G'β, both react; each belonging to adjacent G'βGG'α triplets. These two guests are separated in the unreacted crystal by a distance of 4.9 Å between atoms O(G'β) and F(G'α) (Figures 8 and 12a). After reaction they would be separated by the nearest distance of 5.1 Å (Figure 12b). Thus it would be possible, on this basis, for both of these guest molecules to react.

According to the above packing analysis, G', but not G, can react, which is in excellent agreement with the conclusion derived from the refined occupancies of the various molecular species. Consequently, the product **2** was derived primarily, if not completely, from reaction between guest G' and host, in an arrangement (depicted in Chart I) akin to that in DCA–acetophenone (Scheme I). Of the two G' molecules G'α and G'β there is some doubt as to whether the product from G'α can fit into the channel, suggesting that only G'β reacted. This deduction is in keeping with the least-squares result that 53 ± 3% of the G' molecules reacted.

2.4. Rotation of the Ketyl Radical in the Channel of DCA–Acetophenone. A comparison of the host–guest arrangement of DCA–acetophenone with the absolute configuration *S* about the newly generated chiral center C(OH)(CH_3)C_6H_5 of the photoproduct **1** as found in its own crystal structure[1] (cf. Figure 13 (parts a and c)) shows that the acetyl group of acetophenone undergoes a net rotation of 180° before photoaddition. A similar result is found in DCA–*p*-fluoroacetophenone. A comparison of the molecular structures of the unreacted DCA and the embedded photoproduct **1** (cf. Figure 13 (parts a and b)) shows that the phenyl ring of acetophenone underwent minimal positional change on reaction. It is noteworthy that upon isolation and recrystallization the photoproduct **1** adopts a conformation about the C5–C(OH)$CH_3C_6H_5$ bond radically different from that found in the partially reacted crystal (cf. Figure 13 (parts a and c)). Thus we may infer from the partially reacted crystal that on abstraction of H5 of the steroid atom, the major movement involves the ketyl group of the guest, which undergoes a net rotation of 180° about the C(phenyl)–C(carbonyl) bond before bond formation to atom C5. The remote possibility that the absent

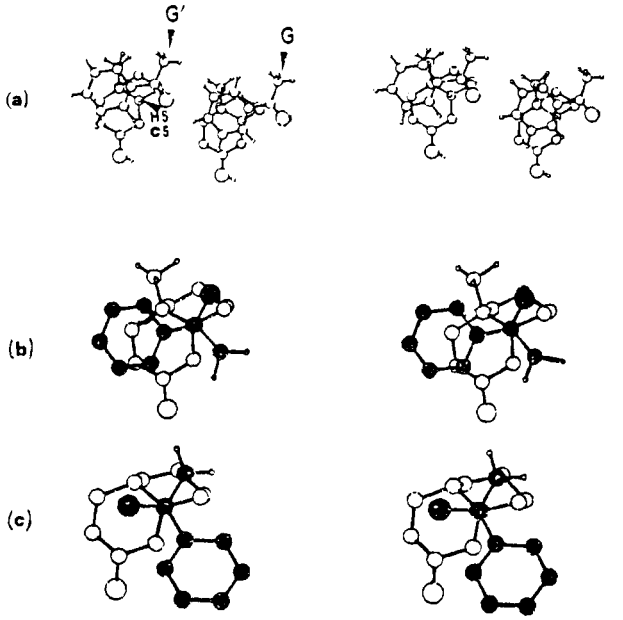


Figure 13. (a) Unreacted DCA–acetophenone complex.[1] Host–guest packing seen along the steroid H–C5 bond. Only ring A of the steroid is shown. (b) The mixed crystal containing DCA host, acetophenone guest, and the addition product **1** as seen along the (C_6H_5)(OH)(CH_3)C–C5 bond. (c) The photoproduct of DCA–acetophenone in its own crystal structure,[1] as seen along the (C_6H_5)(OH)(CH_3)C–C5 bond.

diastereomeric photoproduct of configuration *R* is not formed because of steric hindrance may be dismissed in view of the experimental finding that DCA–propiophenone and DCA–*p*-fluoropropiophenone each yields at site C5 the two diastereomeric photoproducts.[2] Thus the question arose as to whether it would be possible to simulate a net rotation of 180° of the ketyl radical in the channel without inducing prohibitively short host–guest contacts. Consequently, we carried out intermolecular potential energy calculations[4-6] in which the ketyl radical groups C(OH)CH_3 of the guests G and G' were each rotated. The ketyl radical was assumed to adopt a pyramidal geometry[7] with bond angles of 110° about the ketyl C atom. We assumed that in the hydrogen abstraction, only one guest molecule undergoes reaction while its neighboring guest molecules do not. The ketyl radical was rotated about the bond C(ketyl)–C(phenyl) in steps of 20° in the channel for both guests G and G' separately.

Figure 14 depicts a series of frames of the final positions (minimized energy) of the ketyl radical of G and part of its neighboring steroids as the radical undergoes a full rotation. Also included is the reacted guest bound to the steroid for comparison. The change in channel size and shape appears to be minor. In the case of the G' ketyl radical, the final positions appear similar to those of the G ketyl radical and are not thus shown.

The maximum calculated changes in cell dimensions (Figure 15) do not exceed 0.24 Å and 0.8°. These transient changes appear to be sufficiently minor for both G and G' to be able to rotate in the channel prior to the photoaddition step and without incurring any permanent disrupture of the crystal lattice.

The energy curves as function of rotation of the ketyl radicals of G and G' are shown in Figure 16. The ratio of the energy

(3) On the assumption that the van der Waals radii of F and CH are 1.4 and 1.8 Å, respectively.

(4) Intermolecular energy minimizations of these hypothetical models were carried out in the crystal for each angle by using a computer program with most parameters taken from ref 6 and listed in ref 1. Six to seven cycles were required to achieve minimum energy.

(5) Computer program CMIN2, written written by Hagler, A. T., Sharon, R., Dept of Chemical Physics, Weizmann Institute of Science, Rehovot Israel.

(6) Lifson, S.; Hagler, A. T.; Dauber, P. *J. Am. Chem. Soc.* **1979**, *101*, 5131 and references therein.

(7) Because the ketyl radical undergoes a net rotation of 180°, its conjugation with the phenyl ring must be weak during rotation, and so it was reasonable to assume a sp_3 configuration of the radical.

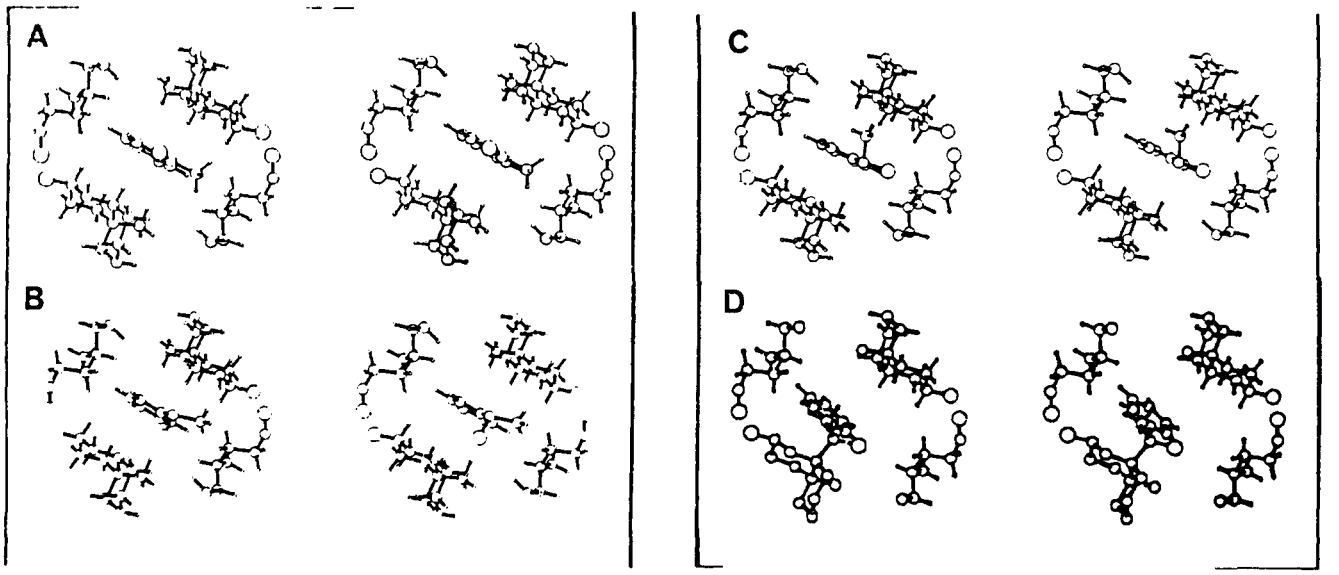


Figure 14. Stereoscopic views of frames of the minimized positions of the ketyl radical G and part of the surrounding neighboring steroid moieties forming the channel wall as the ketyl group rotates about the C(ketyl)–C(phenyl) bond. The first diagram (a) corresponds to the unreacted crystal and the final (d) to the photoproduct **1** in the reacted solid solution.

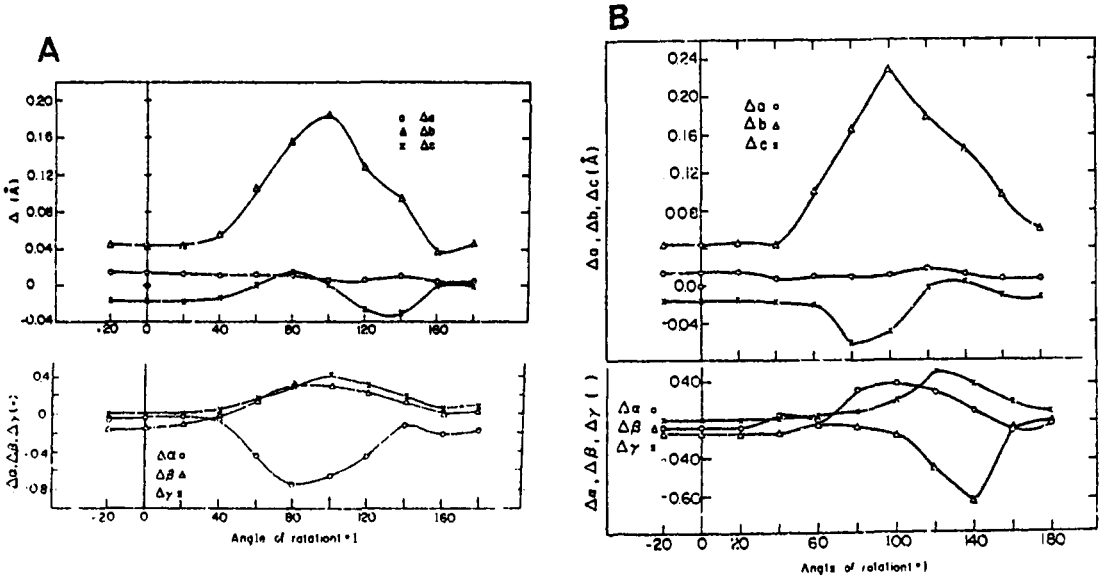


Figure 15. Change in unit cell axes (top) and angles (bottom) as a function of rotation of the acetyl radical of acetophenone: (a) G and (b) G'.

barriers to rotation of G to G', equal to 1:1.7, is compatible with the corresponding photoaddition yields of 50% and 33%, respectively.

2.5. Reaction Pathway. Early theoretical considerations by Zimmerman[8] and Salem[9] suggest that the most favorable orientation for hydrogen abstraction by a carbonyl group is that in the plane of the oxygen n orbital. Sugiyama[10] et al. observed for a particular compound that hydrogen abstraction did not take place where the C–H bond was approximately in the nodal plane of the oxygen n orbital. Studies by Wagner[11] on the photoenolization of *o*-alkyl phenyl ketones indicate that it is the oxygen n orbital which is responsible for hydrogen abstraction by long lived triplets, the rotation around the C(Ph)–C(CO) bond being the rate-determining step. Recent studies by Scheffer[12] on photohydrogen

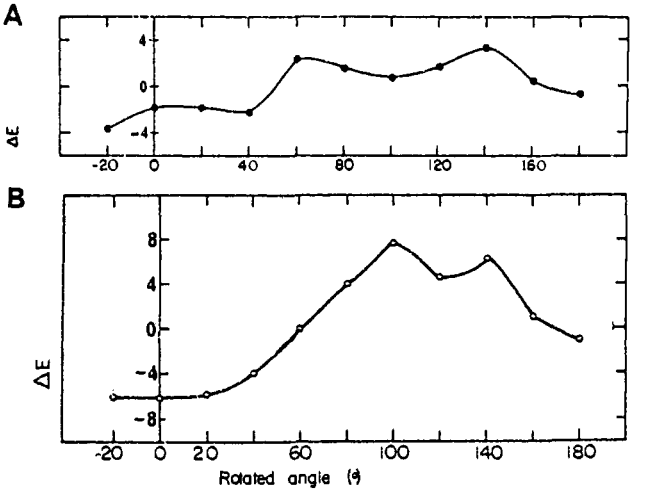


Figure 16. Change in lattice energy E(Kcal/mol) as a function of rotation of the acetyl radical of acetophenone in the channel: (a) guest G, (b) guest G'.

(8) Zimmerman, H. E. *Adv. Photochem.* **1968**, *1*, 118 and references cited therein.
(9) Dauben, W. G.; Salem, L.; Turro, J. N. *Acc. Chem. Res.* **1975**, *8*, 41.
(10) Sugiyama, N.; Nishio, T.; Yamada, K.; Aoyama, H. *Bull. Chem. Soc. Jpn.* **1970**, *43*, 1879.
(11) (a) Wagner, P. J. *Acc. Chem. Res.* **1983**, *16*, 461 and references therein. (b) Wagner, P. J.; Meador, M. A.; Scaiano, J. C. *J. Am. Chem. Soc.* **1984**, *106*, 7989.

Scheme II

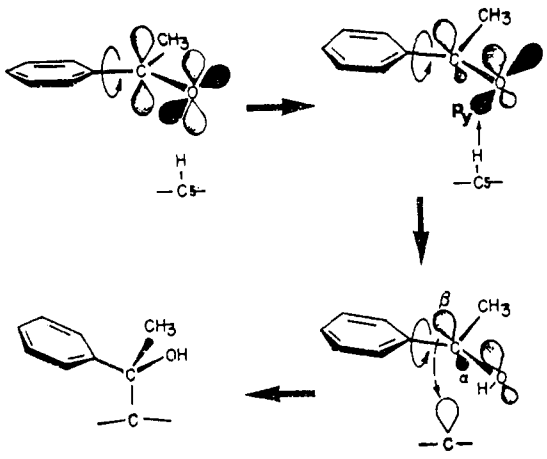


Table I. Cell Constants of (a) DCA–Acetophenone and (b) DCA–*p*-Fluoroacetophenone at −170 °C After Reaction[a,c]

	(a)	(b)
{molecular formula {stoichiometry (i.e., occupancy)		
deoxycholic acid	$\{C_{24}H_{40}O_4$ 0.846 (6)	$\{C_{24}H_{40}O_4$ 0.871 (8)
photoproduct (**1**, **2**)[b]	$\{C_{31}H_{48}O_5$ 0.154 (6)	$\{C_{31}H_{47}O_5F$ 0.129 (8)
guest	$\{C_7H_8O$ 0.232 (17)	$\{C_7H_7OF$ 0.225 (6)
a σ(*a*), (Å)	25.173 (5)	25.155 (7)
b	13.685 (3)	13.679 (6)
c	7.178 (4)	7.135 (2)
V(Å^3)	2472	2455
Z	4	4
space group	$P2_12_12_1$	$P2_12_12_1$
λ (Mo Kα_1)	0.70926	0.70926
D_{calcd} (g·cm^{-3})	1.17	1.18
cryst size (mm)	0.2 × 0.3 × 0.6	0.3 × 0.4 × 0.6

[a] Cell constant at −170 °C before reaction.[1,2] (5:2) DCA–acetophenone: *a* = 25.243 (7), *b* = 13.606 (2), *c* = 7.198 (2) Å; (8:3) DCA–*p*-fluoroacetophenone: *a* = 25.270 (7), *b* = 13.579 (8), *c* = 7.198 (2) Å. [b] Sum of occupancies of DCA + product = 1. [c] Each crystal contains solid solution of host steroid deoxycholic acid (DCA), steroid photoproduct (**1** and **2**, respectively), and guest. Their occupancies as determined by structure-factor least-squares refinement are listed.

abstractions in acetophenones have demonstrated that the angle of hydrogen abstraction by the n orbital was close to ideal. These results are in agreement with our experimental findings, for one way to rationalize the rotation of the acetyl group by 180° during the photoaddition process is to invoke the role played by the Py orbital of the n–π^* excited carbonyl group. In both crystal structures the steroid C5–H (to be abstracted) bond is almost perpendicular to the plane of the guest carbonyl system >C=O and consequently also to the Py orbital of the ketone oxygen. In the light of the photochemical and crystallographic results on pure and partially reacted crystals of the two complexes, we propose that the abstraction of hydrogen involves a rotation of the carbonyl to obtain a better orbital overlap between the Py orbital and C5–H bond (Scheme II). Therefore, the hydrogen abstraction step demands substantial twisting of the acetyl group after excitation. Once the long lived ketyl radical has been formed, it will have enough time to assume the desired favorable orientation for coupling. The formation of single product is indicative of sufficient large energy differences between the two possible rotamers. In addition rotation in the sense shown in Scheme II removes the abstracted hydrogen from the steroid radical. Rotation in the opposite sense might end with regeneration of the starting materials, rather than the other diastereoisomer. The simulated rotation of the ketyl group in the channel of DCA–acetophenone via atom–atom energy potential calculations shows that it is possible to rotate the acetyl group by a net 180° without incurring prohibitively short contacts with the steroid wall.

We may conclude that primarily because these crystals maintain their integrity on photoreaction it was possible to elucidate the molecular pathways of the reactions. This approach is being extended to other DCA–guest complexes in which the photoreactions involve also molecular oxygen included within the channel.

(12) Scheffer, J. R.; Trotter, J.; Omkaram, N.; Evans, S. V.; Ariel, S. *Mol. Cryst. Liq. Cryst.* **1986**, *134*, 169.
(13) Sheldrick, G. M. SHELX program for Crystal Structure Determination, University of Cambridge, England, 1976.
(14) Each rigid group is refined with three translational and three orientational parameters.

Table II. X-ray Intensity Data Collection on UV-Irradiated (a) DCA–Acetophenone and (b) DCA–*p*-Fluoroacetophenone

	(a)	(b)
range (deg)	2–45	2–45
max scan times (s)	120	120
scan mode (ω/θ)	3/2	3/2
no. of monitor reflcns	6	4
no. of reflcns measd	11055	18555
R_m[a]		0.065
no. of indepndnt reflcns	11055	11035

[a] $R_m = \sum w(\bar{F}^2 - F^2)/\sum wF^2$, where F is an observed structure factor, $\bar{F}$ is the weighted mean at a symmetry-related set of F's, and w is the weight of the observed F^2.

Table III. Least-Squares Refinement for (a) DCA–Acetophenone and (b) DCA–*p*-fluoroacetophenone

	(a)	(b)
no. of refined params	309	299
criterion for F_{obsd} exclusn	$F_o < 3\sigma(F_o)$	$F_o < 3\sigma(F_o)$
no. of F_{obsd} used in refinemnt	2701	2327
R[a]	0.088	0.099
R_w[b]	0.089	0.101

[a] $R = \sum|F_o - F_c|/\sum F_o$. [b] $R_w = \sum w^{1/2}|F_o - F_c|/\sum w^{1/2}F_o$, where $w = 1/\sigma^2(F_o)$ [$r = \sum w|F_o - F_c|^2/\sum wF_o^2$ is used in section 3.2 for, the Hamilton test].

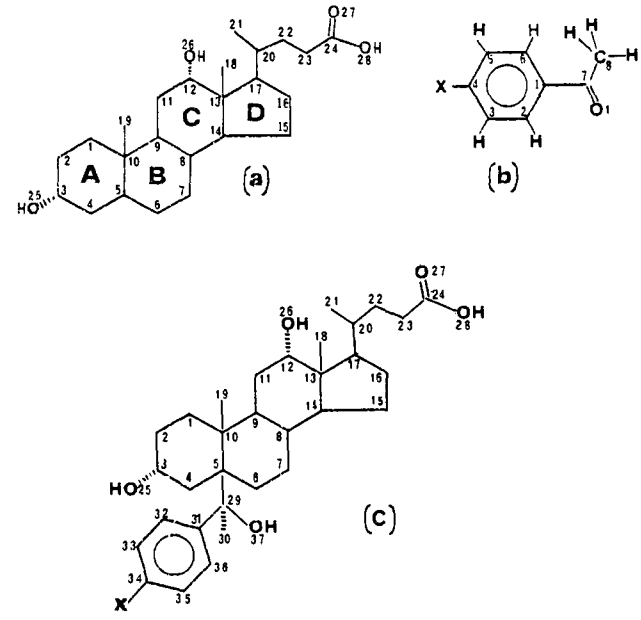


Figure 17. Atom numbering of C and O atoms: (a) host steroid deoxycholic acid (DCA); (b) acetophenone (x = H); *p*-fluoroacetophenone (x = F); (c) photoproduct **1** (x = H); photoproduct **2** (x = F).

3. Experimental Section

3.1. X-ray Structure Determination of Reacted (5:2) DCA–Acetophenone and (8:3) DCA–*p*-Fluoroacetophenone. The X-ray intensities of the crystals of UV-irradiated DCA–acetophenone and DCA–*p*-fluoroacetophenone were measured on a CAD-4 diffractometer by using Mo Kα radiation filtered with a graphite monochromator. The crystals

Table IV. Reacted DCA–Acetophenone (at −170 °C)

atom	*x*	*y*	*z*	U_{eq}	atom	*x*	*y*	*z*	U_{eq}	atom	*x*	*y*	*z*	U_{eq}
(a) Atomic Parameters *x*, *y*, *z* (×10⁴) and U_{eq}[a] (Å² × 10³) of C and O Atoms of Deoxycholic Acid[b]														
C(1)	1261 (1)	2085 (2)	3549 (5)	39	C(10)	1582 (1)	2572 (2)	1968 (5)	30	C(20)	1057 (2)	7631 (4)	512 (8)	34
C(2)	702 (1)	1792 (2)	2988 (5)	37	C(11)	1234 (2)	4287 (3)	2931 (8)	27	C(21)	774 (3)	7680 (5)	2392 (9)	46
C(3)	725 (1)	1087 (2)	1363 (5)	37	C(12)	978 (2)	5246 (3)	2294 (9)	25	C(22)	829 (2)	8398 (4)	−834 (9)	41
C(4)	1023 (1)	1526 (2)	−269 (5)	32	C(13)	1311 (3)	5733 (3)	760 (11)	28	C(23)	254 (2)	8250 (4)	−1428 (9)	46
C(5)	1586 (1)	1860 (2)	275 (5)	36	C(14)	1376 (3)	4981 (3)	−829 (10)	30	C(24)	85 (2)	9041 (4)	−2768 (8)	39
C(6)	1875 (2)	2322 (3)	−1412 (9)	36	C(15)	1623 (3)	5570 (4)	−2409 (12)	36	O(25)	188 (1)	851 (2)	861 (5)	42
C(7)	1659 (3)	3326 (4)	−1930 (7)	35	C(16)	1354 (4)	6580 (4)	−2245 (14)	38	O(26)	450 (2)	5041 (4)	1626 (7)	31
C(8)	1642 (3)	4028 (3)	−276 (9)	30	C(17)	1051 (3)	6586 (4)	−353 (13)	29	O(27)	97 (2)	9906 (3)	−2423 (7)	61
C(9)	1333 (2)	3556 (3)	1353 (7)	26	C(18)	1846 (3)	6061 (4)	1587 (15)	27	O(28)	−90 (1)	8722 (3)	−4354 (6)	42
					C(19)	2149 (1)	2719 (2)	2728 (5)	44					
(b) Atomic Parameters[c] *x*, *y*, *z* (×10⁴) of H atoms of Deoxycholic Acid[d]														
H(1)	1226	2484	4701		H(9)	968	3404	779		H(19′)	2298	2059	3035	
H(1′)	1405	1463	3904		H(11)	1013	4043	3815		H(19″)	2159	3087	3931	
H(2)	473	2334	2558		H(11′)	1583	4448	3464		H(25)	215	572	−314	
H(2′)	486	1458	3924		H(12)	953	5652	3273		H(26)	236	5245	2375	
H(3)	927	430	1647		H(14)	1025	4832	−1273		H(20)	1407	7855	619	
H(4)	1060	1029	−1210		H(15)	2038	5598	−2320		H(21)	973	7467	3215	
H(4′)	824	2055	−828		H(15′)	1550	5200	−3631		H(21′)	466	7321	2303	
H(5)	1780	1245	691		H(16)	1626	7046	−2202		H(21″)	766	8181	2905	
H(6)	1837	1881	−2447		H(16′)	1090	6660	−3379		H(22)	1090	8335	−1979	
H(6′)	2275	2402	−1044		H(17)	685	6385	−592		H(22′)	844	9060	−466	
H(7)	1882	3604	−2973		H(18)	2062	6432	748		H(23)	25	8405	−287	
H(7′)	1303	3270	−2460		H(18′)	2076	5487	1937		H(23′)	200	7535	−2020	
H(8)	2013	4146	215		H(18″)	1798	6429	2633		H(28)	−196	9220	−5195	
					H(19)	2396	3037	1824						
(c) *x*, *y*, *z* Coordinates (×10⁴) of C and O Atoms of Steroid Photoproduct 1[f]														
C(1)	1309	2146	3662		C(14)	1371	4983	−809		C(24)	85 (2)	9041 (4)	−2768 (8)	
C(2)	777	1768	2993		C(15)	1576	5548	−2496		O(27)	97 (2)	9906 (3)	−2423 (7)	
C(3)	854	1037	1444		C(16)	1315	6568	−2293		O(28)	−90 (1)	8722 (3)	−4354 (6)	
C(4)	1182	1489	−127		C(17)	1073	6625	−297		C(29)	2113 (5)	943 (11)	763 (20)	
C(5)	1739	1863	431		C(18)	1907	6081	1381		O(37)	2657 (6)	1209 (16)	456 (27)	
C(6)	1974	2398	−1283		C(19)	2197	2863	3106		C(30)	1960 (11)	204 (21)	−769 (25)	
C(7)	1685	3324	−1872		O(25)	344	755	737		C(31)	2079 (9)	395 (17)	2656 (22)	
C(8)	1664	4053	−261		O(26)	512	5092	1987		C(32)	1699 (9)	−315 (17)	3046 (22)	
C(9)	1393	3581	1432		C(20)	1057 (2)	7631 (4)	512 (8)		C(33)	1671 (9)	−723 (17)	4809 (22)	
C(10)	1669	2607	2136		C(21)	774 (3)	7680 (5)	2392 (9)		C(34)	2018 (9)	−430 (17)	6191 (22)	
C(11)	1322	4341	3004		C(22)	829 (2)	8398 (4)	−834 (9)		C(35)	2397 (9)	274 (17)	5816 (22)	
C(12)	1056	5299	2407		C(23)	254 (2)	8250 (4)	−1428 (9)		C(36)	2428 (9)	688 (17)	4047 (22)	
C(13)	1350	5766	749											
(d) *x*, *y*, *z* Coordinates[g] (×10⁴) of H Atoms of Steroid Photoproduct 1[h]														
H(1)	1231	2651	4646		H(14)	992	4790	−1088		H(20)	1407 (25)	7855 (44)	619 (91)	
H(1′)	1500	1584	4251		H(15)	1471	5231	−3686		H(21)	973 (26)	7467 (45)	3215 (102)	
H(2)	555	2321	2533		H(15′)	1976	5597	−2447		H(21′)	466 (27)	7321 (45)	2303 (93)	
H(2′)	590	1439	4058		H(16)	1579	7054	−2365		H(21″)	766 (26)	8181 (51)	2905 (98)	
H(3)	1045	446	1928		H(16′)	1010	6633	−3285		H(22)	1090 (24)	8335 (43)	−1979 (94)	
H(4)	978	2066	−619		H(17)	735	6372	−570		H(22′)	844 (23)	9060 (44)	−466 (89)	
H(4′)	1230	1004	−1124		H(18)	2104	6504	849		H(23)	25 (24)	8405 (45)	−287 (95)	
H(6)	1962	1940	−2361		H(18′)	2128	5565	2055		H(23′)	200 (23)	7535 (42)	−2020 (93)	
H(6′)	2352	2570	−990		H(18″)	1831	6495	2718		H(28)	−196 (24)	9220 (46)	−5195 (90)	
H(7)	1321	3186	−2272		H(19)	2489	3134	2004		H(30)	1643 (11)	−146 (21)	−1533 (25)	
H(7′)	1888	3642	−2929		H(19′)	2402	2157	3226		H(30′)	1930 (11)	987 (21)	−935 (25)	
H(8)	2046	4227	102		H(19″)	2241	3181	4096		H(30″)	1928 (11)	20 (21)	690 (25)	
H(9)	1025	3427	1012		H(25)	361	537	−218		H(32)	1454 (9)	−515 (17)	2041 (22)	
H(11)	1676	4501	3578		H(26)	291	5221	2390		H(33)	1390 (9)	−1236 (17)	5044 (22)	
H(11′)	1094	4027	4037							H(34)	2009 (9)	−713 (17)	7502 (22)	
H(12)	1047	5781	3475							H(35)	2646 (9)	482 (17)	6824 (22)	
										H(36)	2710 (9)	1204 (17)	3804 (22)	
(e) *x*, *y*, *z* Coordinates (×10⁴) of Acetophenone Molecules:[i] Gα, Gβ, G′α, and G′β														
Acetophenone Gα														
C(4)	2215	−440	5392		C(6)	2819	326	3258		H(5)	3156	719	3054	
C(7)	2648	255	−194		H(1)	1832	−722	1039		C(8)	3163	765	−587	
C(1)	2507	24	1772		H(2)	1569	−1133	4111		H(6)	3188	1402	46	
C(2)	2048	−513	2111		H(3)	2122	−594	6737		H(7)	3201	885	−1940	
C(3)	1905	−742	3916		H(4)	2894	308	6144		H(8)	3469	330	−168	
C(5)	2672	93	5069							O(1)	2357	2	−1451	
Acetophenone Gβ														
C(4)	2261	−427	−5299		C(6)	2837	424	−7410		H(5)	3135	915	−7602	
C(7)	2775	121	−10861		H(1)	2036	−1056	−9656		C(8)	3240	778	−11216	
C(1)	2604	−55	−8893		H(2)	1732	−1393	−6598		H(6)	3184	1441	−10720	
C(2)	2197	−722	−8579		H(3)	2147	−542	−3960		H(7)	3301	846	−12293	
C(3)	2028	−904	−6782		H(4)	2831	579	−4526		H(8)	3567	486	−10344	
C(5)	2665	238	−5607							O(1)	2550	−292	−12132	

Table IV (Continued)

atom	x	y	z	U_{eq}	atom	x	y	z	U_{eq}	atom	x	y	z	U_{eq}
							Acetophenone G′α[j]							
O(1)	2529	−433	9699		C(5)	2680	732	15909		H(4)	2822	1218	16815	
C(7)	2725	160	10753		C(6)	2804	799	14030		H(5)	3042	1353	13599	
C(1)	2603	118	12782		H(1)	2139	−1107	12522		C(8)	3108	915	10062	
C(2)	2278	−629	13427		H(2)	1919	−1244	15721		H(6)	2992	1585	10355	
C(3)	2156	−692	15300		H(3)	2275	−36	17923		H(7)	3145	868	8690	
C(4)	2356	−14	16539							H(8)	3471	790	10643	
							Acetophenone G′β[j]							
O(1)	2386	−232	10162		C(5)	2519	376	16659		H(4)	2718	648	17839	
C(7)	2653	84	11437		C(6)	2727	428	14871		H(5)	3088	748	14689	
C(1)	2445	46	13379		H(1)	1758	−654	12610		C(8)	3200	478	11105	
C(2)	1954	−387	13687		H(2)	1390	−755	15643		H(6)	3239	1155	11549	
C(3)	1746	−435	15469		H(3)	1892	−77	18280		H(7)	3282	474	9755	
C(4)	2030	−55	16952							H(8)	3468	43	11764	

[a] $U_{eq} = {}^1/_3\sum_{ij}U_{ij}a_ia^*_j$. [b] The average $\sigma(U_{eq})$ = 0.003 Å^2. [c] Atoms H(1)···H(26) refined as part of rigid body of steroid (see Table IVa). Atoms H(20)···H(28) of steroid side chain refined freely. For these atoms average $\sigma(x)$, $\sigma(y)$, $\sigma(z)$ = 25, 47, 95 (×10^4), respectively. [d] U of atoms H(1)···H(26) = 0.042 (3) Å^2, U of atoms H(20)···H(28) is 0.056 (6) Å^2. [e] Photoproduct 1 fragment C(1)···O(26) refined as rigid body; for each atom $\sigma(x)$, $\sigma(y)$, $\sigma(z)$ = 5, 11, 20 (×10^4), respectively. Side chain C(20)···O(28) refined freely and assumed to coincide with corresponding atoms of deoxycholic acid (Table IVa). The moiety C(29)···C(36) refined with constraints. [f] U_{eq} of atoms C(1)···O(28) as in Table IVa. Isotropic U of atoms C(29)···C(36) fixed at 0.05 Å^2. [g] H atoms H(1)···H(26) refined as part of rigid body (see Table IVc); $\sigma(x)$, $\sigma(y)$, $\sigma(z)$ = 5, 11, 20 (×10^4), respectively. H(20)···H(28) of photoproduct side chain refined freely and assumed to coincide with corresponding atoms of deoxycholic acid (Table IVb). H(30)···H(36) refined with constraints. [h] The H atoms H(1)···H(26) refined with isotropic U = 0.042 (3) Å^2. U of side chain H atoms H(2)···H(28) = 0.056 (6) Å^2. U of H atoms H(30)···H(36) fixed at 0.05 Å^2. [i] The isotropic U of all atoms is fixed at 0.065 Å^2. [j] All four guest molecules refined as rigid bodies; $\sigma(x)$, $\sigma(y)$, and $\sigma(z)$ (×10^4) of Gα, Gβ, G′α, and G′β are [41, 91, 46], [36, 46, 47], [67, 120, 62], and [32, 70, 36], respectively.

were cooled to ca. −170 °C. The cell dimensions of each crystal (Table I) were determined by least-squares by using 25 reflections. The essential details on the intensity data collection are given in Table II. The X-ray intensities of many reflections of these two crystals had changed significantly on UV irradiation which indicated distinct changes in crystal structure. In addition there were far fewer observed reflections after UV irradiation indicative of a solid solution in the reacted crystal. For both complexes structural least-squares refinement using SHELX[13] was initiated with the refined atomic coordinates of the unreacted structures.[1,2] The atomic numbering is given in Figure 17.

Reacted DCA–acetophenone refined to R = 0.20. A difference map yielded four distinct peaks within the channel near the reactive site C5 of the steroid. These peaks were sufficiently removed from the plane of the unreacted guest molecules in the channel to appear in a segment of space relatively free of electron density in the reacted crystal. Their peak heights ranged from 0.7 to 0.9 e/Å^3. The refined thermal parameters of the DCA molecule were distinctly higher than those of the unreacted crystal structure,[1] (averaged values of 0.045 vs. 0.022 Å^2), indicative of a solid solution in the reacted crystal.

DCA–*p*-fluoroacetophenone behaved likewise. Refinement yielded R = 0.15. A difference map displayed within the channel four distinct peaks of height 0.6–0.7 e/Å^3 arranged relative to the steroid in almost the same way as in reacted DCA–acetophenone. Also the refined thermal parameters of DCA (av 0.048 Å^2) were decidedly higher than those of the unreacted crystal structure[2] (av 0.025 Å^2).

Thus we deduced that in both reacted crystals the unreacted and reacted steroid molecules do not occupy exactly identical sites. This lack of atomic coincidence was taken care of in the least-squares process by refining the four fused rings, A, B, C, D, and immediate substituents of the steroid as a rigid group.[14] In addition, identical atoms of the reacted and unreacted steroids were assigned the same temperature factor. The geometry of the rigid fragment of the unreacted steroid DCA was taken from the crystal structure of the unreacted complex,[1] that of the reacted steroid from the room temperature crystal structure of the isolated photoproduct **1**, naturally excluding the moiety $C(OH)(C_6H_5)CH_3$. The corresponding atoms of the steroid side chain of DCA and the photoproduct were assumed to coincide because of conformational flexibility. In both reacted crystal structures the four peaks were located in the channel. P1, P2, P3, P4, and the (unreacted) steroid atom C5 corresponded very nicely in tetrahedral geometry to the new chiral carbon atom (P1) of the photoproduct and the four atoms to which P1 is bonded, namely oxygen, C(methyl), C(phenyl), and atom C5. Since the chiral carbon atom P1 was unambiguously assigned, the problem was to decide which atom, i.e., oxygen, C(methyl), C(phenyl), corresponded to which remaining peak, P2, P3, P4. Actually the problem was to locate the phenyl ring.

3.2. Further Refinement of UV-Irradiated DCA–Acetophenone. Inspection of the peak system P1–P4 and the neighboring (unreacted) host and guest molecules, shown in Chart II, indicated that P2 must be the phenyl atom C1 of acetophenone, after reaction. Firstly, P2 is much closer to the atom C1 than either P2 or P3. Secondly, the plane defined by the three atoms (C5 (host), C1 (guest), C7 (guest)) is almost coplanar with the atoms C5, P1, P2. Thirdly, assuming either peak P3 or P4 to be the phenyl atom C1 would necessitate a rotation of approximately

Chart II

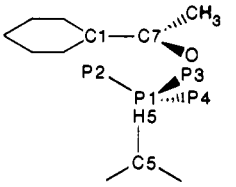
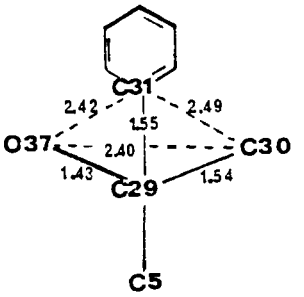


Chart III



120° of the phenyl rings of G and G′ about the C5–P1 bond to reach the positions specified by either of these two peaks. Either rotation would induce prohibitively short contacts with the channel walls. Moreover, because of short host–guest contacts, the atom C1 of the guest phenyl ring cannot even be placed at either position P3 or P4, in particular at P3 so that the corresponding model is absolutely precluded. Thus two models were tested by structure factor least squares on reacted DCA–acetophenone in which the phenyl ring was inserted into positions as defined by peaks P2 and P4.

The chiral group $C(C_6H_5)(OH)CH_3$ attached to C5 of the product **1** was refined as follows. The rigid fragment of the steroid product was made to include the chiral carbon C29. The phenyl ring was refined as a rigid body, and the hydroxy oxygen O37 and the methyl carbon C30 were refined freely but with constraints imposed on interatomic distances as shown in Chart III. In the final stages of refinement the rigid body constraint on the C and O atoms of unreacted DCA (i.e., rings A,B,C,D) was replaced by restraints imposed on interatomic 1–2 (i.e., bond) and 1···3 distances.

Refinement ruled out the phenyl being attached to P4, because the ring made too short a contact with the channel wall. In addition this model **1** yielded significantly larger R factors (defined in Table III) than model **2** in which the phenyl ring was specified by peak P2 (R_1 = 0.0941 vs. R_2 = 0.0876, R_{w1} = 0.0094, R_{w2} = 0.088, and r_1 = 0.114 vs. r_2 = 0.103). Applying the Hamilton test[15] we compare R = 0.114/0.1029 = 1.082, and $R_{b,n-m,\alpha} = R_{6,2701-291,0.005}$ = 1.0039, where b represents the six positional parameters of the phenyl ring refined as a rigid body, n equals the number of reflections, m is the number of parameters, and α is the

(15) Hamilton, W. C. *Acta. Crystallogr.* **1965**, *18*, 502.

Table V. Reacted DCA–*p*-Fluoroacetophenone

atom	*x*	*y*	*z*	U_{eq}	atom	*x*	*y*	*z*	U_{eq}	atom	*x*	*y*	*z*	U_{eq}
(a) Atomic Parameters *x*, *y*, *z* (×10⁴) and U_{eq}[a] (Å² × 10³) of C and O Atoms of Deoxycholic Acid (The Average σ (U_{eq}) = 0.004 Å²)														
C(1)	1279 (2)	2056 (4)	3607 (7)	50	C(10)	1604 (2)	2544 (4)	2039 (7)	40	C(20)	1054 (3)	7597 (5)	606 (11)	41
C(2)	723 (2)	1757 (4)	3021 (7)	41	C(11)	1237 (3)	4249 (4)	2997 (11)	33	C(21)	759 (4)	7652 (6)	2480 (12)	46
C(3)	754 (2)	1050 (4)	1399 (7)	41	C(12)	981 (3)	5207 (4)	2351 (12)	27	C(22)	825 (3)	8363 (5)	−791 (13)	46
C(4)	1057 (2)	1491 (4)	−221 (7)	44	C(13)	1319 (3)	5703 (4)	833 (15)	30	C(23)	250 (3)	8210 (6)	−1388 (13)	52
C(5)	1617 (2)	1831 (4)	349 (7)	48	C(14)	1389 (4)	4957 (4)	−771 (13)	32	C(24)	85 (3)	8997 (5)	−2729 (11)	44
C(6)	1903 (3)	2300 (5)	−1345 (13)	45	C(15)	1635 (4)	5555 (5)	−2352 (16)	44	O(25)	220 (2)	808 (4)	873 (7)	48
C(7)	1687 (4)	3304 (5)	−1871 (10)	48	C(16)	1355 (4)	6557 (5)	−2195 (19)	40	O(26)	455 (3)	4999 (5)	1657 (10)	36
C(8)	1660 (3)	4002 (4)	−200 (13)	35	C(17)	1059 (4)	6559 (5)	−281 (17)	30	O(27)	114 (3)	9875 (4)	−2439 (9)	74
C(9)	1344 (3)	3519 (4)	1414 (10)	31	C(18)	1850 (4)	6033 (5)	1688 (21)	32	O(28)	−109 (2)	8677 (3)	−4317 (8)	48
					C(19)	2168 (2)	2697 (4)	2826 (7)	50					
(b) Atomic Parameters[b] *x*, *y*, *z* (×10⁴) of H Atoms of Deoxycholic Acid (Isotropic *U* of Atoms H(1)···H(26) = 0.045 (4) Å², *U* of Atoms H(20)···H(28) = 0.063 (9) Å²)														
H(1)	1238	2456	4756		H(9)	992	3370	819		H(19′)	2318	2040	3142	
H(1′)	1424	1436	3971		H(11)	1024	4012	3855		H(19″)	2172	3067	4028	
H(2)	494	2296	2579		H(11′)	1594	4421	3529		H(25)	252	529	−300	
H(2′)	504	1421	3948		H(12)	961	5620	3305		H(26)	249	5204	2375	
H(3)	957	396	1695		H(14)	1053	4796	−1235		H(20)	1373	7798	631	
H(4)	1099	993	−1158		H(15)	2067	5572	−2237		H(21)	952	7367	3367	
H(4′)	859	2018	−790		H(15′)	1585	5168	−3569		H(21′)	469	7447	2408	
H(5)	1811	1219	776		H(16)	1650	7016	−2142		H(21″)	661	8281	3325	
H(6)	1878	1852	−2361		H(16′)	1120	6623	−3343		H(22)	1128	8389	−1726	
H(6′)	2309	2379	−939		H(17)	705	6346	−574		H(22′)	818	9045	−573	
H(7)	1920	3575	−2890		H(18)	2077	6408	829		H(23)	32	8336	−288	
H(7′)	1340	3236	−2404		H(18′)	2089	5464	2023		H(23′)	163	7515	−2020	
H(8)	2038	4121	301		H(18″)	1806	6405	2702		H(28)	−66	9084	−5866	
					H(19)	2418	3018	1932						
(c) *x*, *y*, *z* Coordinates[c] (×10⁴) of C and O Atoms of Steroid Photoproduct **2** (U_{eq} of Atoms C(1)···O(28) as in Table V; Isotropic *U* of Atoms C(29)···F(34) = 0.076 (9) Å²)														
C(1)	1271	2055	3724		C(14)	1311	4953	−607		C(24)	85 (3)	8997 (5)	−2729 (11)	
C(2)	750	1655	2994		C(15)	1517	5551	−2250		O(27)	114 (3)	9875 (4)	−2439 (9)	
C(3)	849	950	1417		C(16)	1238	6552	−2021		O(28)	−109 (2)	8677 (3)	−4317 (8)	
C(4)	1180	1441	−104		C(17)	982	6569	−44		C(29)	2113 (12)	938 (24)	837 (41)	
C(5)	1726	1840	517		C(18)	1813	6051	1677		O(37)	2653 (15)	1208 (35)	457 (59)	
C(6)	1962	2410	−1152		C(19)	2149	2830	3274		C(30)	1961 (25)	131 (44)	−576 (58)	
C(7)	1661	3327	−1721		O(25)	348	648	656		C(31)	2092 (18)	471 (33)	2821 (44)	
C(8)	1617	4033	−79		O(26)	433	4974	2122		C(32)	1722 (18)	−243 (33)	3294 (44)	
C(9)	1343	3523	1568		C(20)	1054 (3)	7597 (5)	606 (11)		C(33)	1729 (18)	−660 (33)	5063 (44)	
C(10)	1632	2556	2249		C(21)	759 (4)	7652 (6)	2480 (12)		C(34)	2102 (18)	−369 (33)	6371 (44)	
C(11)	1249	4258	3170		C(22)	825 (3)	8363 (5)	−791 (13)		C(35)	2472 (18)	341 (33)	5912 (44)	
C(12)	970	5208	2595		C(23)	250 (3)	8210 (6)	−1388 (13)		C(36)	2467 (18)	762 (33)	4137 (44)	
C(13)	1267	5712	985							F(34)	2105 (18)	−736 (33)	8087 (44)	
(d) *x*, *y*, *z* Coordinates[d] (×10⁴) of H Atoms of Steroid Photoproduct **2** (Isotropic *U* of H Atoms H(1)···H(26) = 0.045 (4) Å²; *U* of atoms H(20)···H(28) = 0.063 (9) Å²; *U* of Atoms H(30)···H(36) = 0.076 (9) Å²)														
H(1)	1177	2542	4724		H(12)	946	5674	3685		H(21)	952	7367	3367	
H(1′)	1467	1497	4301		H(14)	938	4741	−926		H(21′)	469	7447	2408	
H(2)	521	2201	2541		H(15)	1426	5244	−3463		H(21″)	661	8281	3325	
H(2′)	562	1302	4027		H(15′)	1916	5622	−2166		H(22)	1128	8389	−1726	
H(3)	1047	364	1889		H(16)	1494	7054	−2052		H(22′)	818	9045	−573	
H(4)	968	2012	−586		H(16′)	939	6613	−3047		H(23)	32	8336	−288	
H(4′)	1242	973	−1119		H(17)	650	6300	−356		H(23′)	163	7515	−2020	
H(6)	1965	1967	−2252		H(18)	2007	6493	1181		H(28)	−66	9084	−5866	
H(6′)	2335	2601	−820		H(18′)	2039	5540	2345		H(30)	1754	−51	−1856	
H(7)	1302	3173	−2157		H(18″)	1722	6443	3026		H(30′)	1760	−205	598	
H(7′)	1865	3671	−2746		H(19)	2443	3133	2209		H(30″)	2364	−136	−649	
H(8)	1993	4224	323		H(19′)	2365	2136	3378		H(32)	1458	−442	2342	
H(9)	982	3353	1111		H(19″)	2181	3137	4282		H(33)	1454	−1176	5360	
H(11)	1597	4431	3780		H(25)	376	444	−307		H(35)	2740	546	6866	
H(11′)	1020	3917	4169		H(26)	208	5086	2512		H(36)	2742	1281	3832	
					H(20)	1373	7798	631						
(e) *x*, *y*, *z* Coordinates of Guest Molecules (Isotropic *U* of All Atoms Refined to 0.15 (1) Å²)														
p-Fluoroacetophenone G														
F(1)	1936	−597	5217		C(5)	2724	−488	3502		H(5)	3387	−367	1798	
C(7)	2985	492	−1389		C(6)	2991	−230	1865		C(8)	3576	383	−1540	
C(1)	2716	203	384		H(1)	1984	679	−491		H(6)	3690	−294	−1347	
C(2)	2175	363	564		H(2)	1516	247	2282		H(7)	3699	589	−2804	
C(3)	1911	113	2202		H(4)	2919	−799	4567		H(8)	3756	818	−572	
C(4)	2185	−316	3665							O(1)	2726	840	−2665	
p-Fluoroacetophenone G′														
F(1)	1845	−431	7982		C(5)	2478	296	6034		H(5)	3020	864	4122	
C(7)	2678	112	774		C(6)	2693	433	4256		C(8)	3134	800	472	
C(1)	2462	−13	2709		H(1)	1855	−909	1838		H(6)	3446	618	1215	
C(2)	2015	−598	2953		H(2)	1477	−1160	4852		H(7)	3241	799	−869	
C(3)	1803	−730	4726		H(4)	2642	615	7154		H(8)	3021	1491	821	
C(4)	2033	−286	6264							O(1)	2474	−315	−535	

Table V (footnotes)

[a] $U_{eq} = {}^1/_3\sum_{ij}U_{ij}a_ia^*_j$. [b] Atoms H(1)···H(26) refined as part of rigid body of steroid (see Table Va). For these atoms $\sigma(x)$, $\sigma(y)$, $\sigma(z)$ = 1, 2, 5 ($\times 10^4$), respectively. Atoms H(20)···H(28) of steroid side chain refined freely. For these atoms average $\sigma(x)$, $\sigma(y)$, $\sigma(z)$ = 35, 60, 120 ($\times 10^4$), respectively. [c] Photoproduct **2** fragment C(1)···O(26) refined as rigid body; for each atom $\sigma(x)$, $\sigma(y)$, $\sigma(z)$ = 12, 24, 41 ($\times 10^4$), respectively. Side chain C(20)···O(28) refined freely and assumed to coincide with corresponding atoms of deoxycholic acid (Table Va). Moiety C(29)···F(34) refined with constraints. [d] H atoms H(1)···H(26) refined as part of rigid body (see Table Vc); $\sigma(x)$, $\sigma(y)$, $\sigma(z)$ = 12, 24, 41 ($\times 10^4$), respectively. H(20)···H(28) of photoproduct side chain refined freely (see Table Vb). H atoms H(30)···H(36) refined with constraints.

significance level. Thus we can reject the hypothesis at even less than the 0.005 level, the structure yielding the higher r value. The final phenyl position of model **2** was eventually confirmed after final refinement by a stepwise difference synthesis removing each of the phenyl atoms in the structure factor calculation and finding these atoms in turn as distinct peaks in the resulting difference map. Their peak heights ranged from 0.8 to 1.0 e/Å^3.

The refined occupancies for model **2** of the rigid body moieties of photoproduct **1**, of unreacted DCA (i.e., rings A, B, C, D, and immediate substituents), and of the acetophenone molecules G and G′ were 0.154 (6), 0.846 (6), 0.093 (5), and 0.132 (5), respectively. The sum of the occupancies of the rigid fragments of DCA and **1** were constrained to a value of one.

The intermolecular contacts between the photogenerated moiety C(OH)$C_6H_5(CH_3)$ of product **1** and its neighboring unreacted G and G′ molecules are short: 2.77 Å for C(G′)···C(photoproduct **1**) and 2.92 Å for C4(G)···C(photoproduct **1**).

These results indicate that this refined model is not entirely correct. They may be explained and the model improved as follows: First if both G and G′ molecules of a close-packed pair (see Figure 2) react, then prohibitively short contacts would occur between the reacted guests (Figure 7). Thus in a given close-packed pair, either G or G′ may react but not both. Secondly, the separation between G and G′ guest molecules of a close-packed pair in the reacted crystal is 0.15 Å greater than in the unreacted crystal[1] [i.e., C(G′)···C4(G) = 3.33 (1) vs 3.18 (1) Å]. We therefore suggest that there are two possible positions for each of the guests G and G′. If the guest molecules G and G′ of a close-packed pair are both unreacted, they are separated by the distance of 3.18 Å as found in the unreacted crystal. If either G or G′ of this pair reacts then the remaining unreacted guest, G′ or G, respectively, adjusts its position along the channel axis to make favorable intermolecular contacts with the reacted guest. On this basis there are two locations for each of the guests G and G′ in the channel, and we obtained a larger separation between G and G′ in the reacted crystal, because we assumed that these guests each have only one crystallographic position in the unit cell. Thus we inserted into the least-squares refinement four guest molecules Gα, Gβ, G′α, and G′β. The symbol α specifies a guest molecule in a close-packed pair whose neighbor is unreacted; and β a guest whose original neighbor in a close-packed pair has reacted. Both molecules of the close-packed pair Gα and G′α were assigned the same thermal parameter and must have the same occupancy factor. Furthermore, we constrained the separation distance between O(G′α) and C4(Gα) to 3.18 Å as in the unreacted crystal. For the guest molecules Gβ and G′β, we restrained the distances between Gβ, or G′β and its reacted guest neighbor, G′, or G, respectively (both of which originally belonged to a close-packed pair), to reasonable values [i.e., O1(G′β)···C34 (**1**) = 3.2 Å and C4(Gβ)···C30 (**1**) = 3.4 Å]. The occupancies of Gβ and G′β do not have to be the same, because these two molecules do not react to the same extent.

The occupancies of Gβ, G′β and the pair (Gα and G′α) refined to 0.056 (10), 0.090 (7) and 0.043 (8), respectively. The occupancies of the unreacted and reacted steroids were kept fixed at their original refined values of 0.8465 and 0.1535, respectively. Values of R = 0.087 and R_w = 0.088 were obtained. The sum 0.043 (8) + 0.056 (10) = 0.099 (13) is close to 0.093 the original occupancy for guest G, and 0.043 (8) + 0.090 (7) = 0.133 (11) is close to 0.132 the original value for G′. The extent of photoconversion of both G and G′ acetophenone molecules may be derived from the reduction in occupancy of the guest molecules from the value of 0.40 (1) in the unreacted crystal to 0.232 (17) [=0.099 (13) + 0.133 (11)] to yield a photoconversion value of 0.168 (20)/0.40 (1) = 0.42 (5). The photoconversion may also be derived independently from the occupancy of 0.154 (6) of the reacted steroid, resulting in a guest photo yield of 0.154 (6)/0.40 (1) = 0.385 (15). These two results are satisfyingly close to each other, yielding a mean guest photoconversion of 40%.

According to this final refinement there are three different close-packed pair arrangements in the channel involving reacted and unreacted guests (Figure 5 (parts a–c)): (a) The close-packed pair Gα and G′α with individual occupancy 0.043. The intermolecular distance between O(G′α) and C4(Gα) is 3.18 Å, as in the G G′ pair in the unreacted crystal structure. (b) The photoaddition product **1** and the unreacted molecule Gβ with occupancy 0.056, where G′ has reacted. The contact between C30(**1**) and C4(Gβ) is 3.4 Å. The guest molecule Gβ is shifted away from its original location occupied by Gα. (c) The photoaddition product **1** and the unreacted molecule G′β with occupancy 0.09. Here G has reacted, but not G′. The contact between O(G′β) and C34(**1**) is 3.2 Å. The guest molecule G′β is shifted away from its original location occupied by G′α.

Figure 6 displays the structure of this irradiated crystal which contains product of **1**, unreacted DCA, and unreacted acetophenone molecules Gα, Gβ, G′α, and G′β.

3.3. Further Refinement of UV-Irradiated DCA–*p*-Fluoroacetophenone. We constructed the starting model of the product molecule **2** from the refined product molecule **1** by simply adding the fluorine atom substituent to C34. The refinement was akin to that adopted for reacted DCA–acetophenone.

The sum of the occupancy factors of the photoproduct and unreacted rigid steroid moieties (i.e., rings A, B, C, D, and immediate substituents) were constrained to a value of one. The atoms of the steroid side chain were refined freely. The refined occupancy factors of rigid moieties of the photoproduct **2**, unreacted DCA, and the unreacted *p*-fluoroacetophenone molecules G′ and G were 0.129 (8), 0.871 (8), 0.118 (5), and 0.107 (4), respectively. R = 0.099 and R_w = 0.101 were obtained.

4. Results

Details on the refinements are given in Table III. The positional atomic parameters x, y, z and isotropic temperature factors (U_{eq}, U_{iso}) are given in Tables IV and V for DCA–acetophenone and DCA–*p*-fluoroacetophenone, respectively.

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Registry No. 1, 95586-16-6; **2**, 80659-96-7; (5:2) DCA–acetophenone, 83035-58-9; (8:3) DCA–*p*-fluoroacetophenone, 83035-62-5.

Supplementary Material Available: All bond lengths and bond angles and the anisotropic thermal parameters of the steroid molecules are given in Tables 4S and 5S (16 pages). Ordering information is given on any current masthead page.