The Chemistry of Santonene. Part VIII.[1] Photoreaction of 4α*H*-Pyrosantonin

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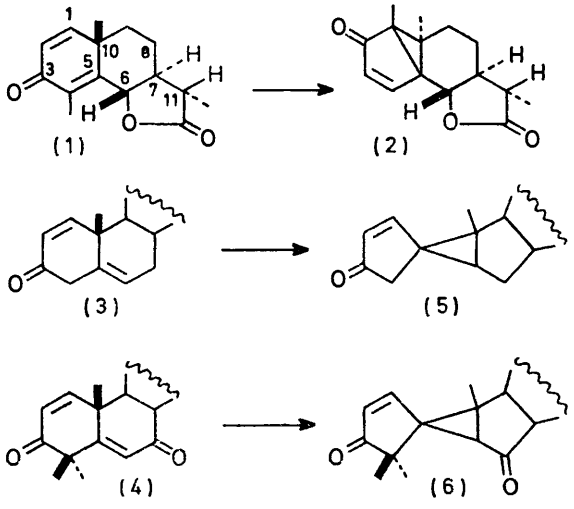
Irradiation of 4α*H*-pyrosantonin [(11*S*)-3-oxo-4α*H*-eudesma-1,5-dien-12,6-olactone] (7) affords four isomeric photopyrosantonins A—D [(9)—(12)], each possessing a spiro(bicyclo[3.1.0]hexane)-6,1'-cyclopentane skeleton. The two *trans*-fused lactones A and D [(9) and (12)] are readily hydrolysed to give the same diketo-acid (17a) with opening of the lactone and cyclopropane rings. The *cis*-fused lactones, B and C [(10) and (11)] are more stable but on treatment with acid afford the diketo-acid (18a). The *cis*-lactones can be equilibrated photochemically and by acid. The *trans*-lactones can be equilibrated photochemically. Pyrolysis of dihydro-derivatives of the *trans*-lactones affords the corresponding derivatives of the *cis*-lactones. The mechanism of the photochemical reaction is discussed; the pathway from the *trans*-lactone to the diketo-acid (17) has been followed by use of a deuterium-labelling technique.

STUDIES of the photochemical rearrangements of santonin (1) have involved both structural elucidation of the products, and also investigation of the mechanisms involved. For example the santonin–lumisantonin [(1) ⟶ (2)] photoreaction,[2-5] has proved to be typical of cyclohexa-2,5-dienones.[6] Recently Schaffner, Jeger, *et al.*, have examined the photochemical reactions of the steroidal 1,5-dien-3-ones (3) [7,8] and (4),[9] and have shown that the products from (3) include four stereoisomers of



gross structure (5). Compound (4) affords two isomers of structure (6).

We have recently shown [10] that pyrolysis of santonin [5] affords 4α*H*-pyrosantonin (7), and have subsequently found that 4β*H*-pyrosantonin (8) is a minor component in the reaction mixture.[11] We now describe the photochemical products derived from 4α*H*-pyrosantonin by use of a medium-pressure Hanovia mercury lamp and a Pyrex filter, and with tetrahydrofuran, ether, or benzene as solvent.

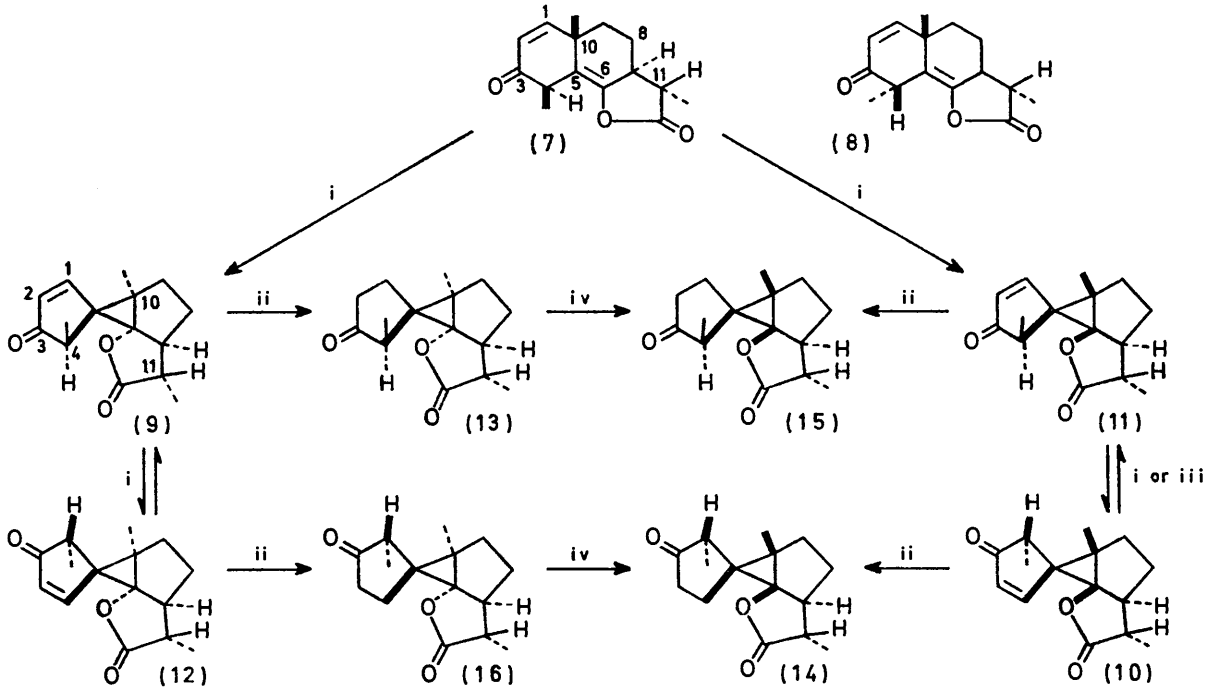
The products, photopyrosantonins A—D [(9)—(12), respectively] can be separated by careful column chromatography over silica or by thick-layer chromatography. Photopyrosantonin D (12), has not been obtained in a pure state, but its n.m.r. spectrum has been deduced from that of a mixture with (11), obtained by thick-layer chromatography. With this limitation, all the four products have been shown to possess similar physical properties and appear to be stereoisomers. To take the isomer A (9) as an example, its n.m.r. spectrum (see Experimental section) shows the presence of an angular methyl group, two secondary methyls, and two vinyl protons in a cyclopentenone ring (*cf.* ref. 12). The i.r. spectrum confirms the presence of the cyclopentenone ring, and shows the presence of a γ-lactone. The u.v. spectrum ($\lambda_{max.}$ 255 nm) indicates that the

[1] Part VII, D. F. Rane and T. B. H. McMurry, *J. Chem. Soc.* (*C*), 1971, 3851.
[2] D. H. R. Barton, P. de Mayo, and M. Shafiq, *J. Chem. Soc.*, 1958, 3314; D. Arigoni, H. Bosshard, H. Burderer, G. Büchi, O. Jeger, and L. J. Krebaum, *Helv. Chim. Acta*, 1957, **40**, 1732.
[3] H. E. Zimmerman, *Adv. Photochem.*, 1963, **1**, 183.
[4] M. H. Fisch and J. H. Richards, *J. Amer. Chem. Soc.*, 1963, **85**, 3029; D. I. Schuster and A. C. Fabian, *Tetrahedron Letters*, 1968, 1301; M. H. Fisch, *Chem. Comm.*, 1969, 1472; G. March, D. R. Kearns, and M. Fisch, *J. Amer. Chem. Soc.*, 1970, **82**, 2252.
[5] K. Schaffner-Sabba, *Helv. Chim. Acta*, 1969, **52**, 1237.
[6] P. J. Kropp in 'Organic Photochemistry,' ed. O. L. Chapman, Arnold, London, 1967, p. 1; K. Schaffner, *Adv. Photochem.*, 1967, **4**, 81.
[7] B. Nann, D. Gravel, P. Shorta, H. Wehrli, K. Schaffner, and O. Jeger, *Helv. Chim. Acta*, 1963, **46**, 2473.
[8] B. Nann, H. Wehrli, K. Schaffner, and O. Jeger, *Helv. Chim. Acta*, 1965, **48**, 1680.
[9] S. Domb and K. Schaffner, *Helv. Chim. Acta*, 1970, **53**, 1765.
[10] T. B. H. McMurry and D. F. Rane, *J. Chem. Soc.* (*C*), 1971, 1389.
[11] K. Ishikawa and T. B. H. McMurry, unpublished results.
[12] L. M. Jackman and S. Sternhell, 'Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry,' Pergamon, Oxford, 2nd edn., 1969, pp. 188, 303.

cyclopentenone chromophore is further conjugated, possibly with a cyclopropane ring, by analogy with the steroid analogues.[7-9] All four isomers can be hydrogenated to give the dihydro-derivatives (13)—(16), respectively.

Two of the isomeric structures, (9) and (12), possess 6,7-*trans*-fused lactone rings,* and two possess *cis*-fused lactone rings. The *trans*-fused lactones are highly strained and indeed their structures cannot be constructed with Dreiding models. Only two authenticated examples of compounds with five-membered lactone rings fused *trans* to a cyclopentane ring system have been reported,[13,14] and these compounds are very reactive. In practice, two of the photoisomers from pyrosantonin are labile to water and other hydroxylic solvents, and two are less reactive. The labile isomers, A and D, can be assigned the structures (9) and (12) with *trans*-fused lactone systems; the more stable isomers, B and C, can be assigned structures (10) and (11). We provide evidence later to justify the assignment of structure (10) to B, and of (11) to C.

Both *trans*-lactones A and D on hydrolysis followed by treatment with acid afford the same keto-acid (17a) (see later); both *cis*-lactones B and C on treatment with acid afford a different keto-acid (18a). This confirms that lactones A and D possess the same stereochemistry at the 10- and consequently at the 6-position. The c.d. spectra of compounds (17a) and (18a) are almost mirror images, as would be expected of near enantiomers. If the c.d. peaks at 305—306 nm are caused by the $n \longrightarrow \pi^*$ transition in the 4,5-β,γ-unsaturated 6-ketone chromophore, the sign predicts the correct stereochemistry at the 10-position.[15] These particular c.d. peaks are unlikely to be due to the ring A cyclopentenone system, as this latter chromophore would be expected to show peaks at a higher wavelength. The fact that only very small peaks appear at higher wavelengths can be explained by the planar nature of the chromophore.



Reagents: i, *hν*; ii, H_2–Pd; iii, H^+, iv, heat, 250°

On photolysis, the two *cis*-fused lactones (10) and (11) equilibrate, as do the two *trans*-fused lactones (9) and (12). Schaffner, Jeger, *et al.*[7,8] have noted a similar equilibration in the corresponding steroid series, and postulate that it is achieved through a 5,10-diradical intermediate. In our case, the intermediate could be either the 5,10- (19) or the 5,6-diradical (20). This equilibration explains the formation of four products in the photolysis of pyrosantonin. Only two of the isomers, (9) and (11), can be formed in a symmetry-allowed photochemical process,[16] the other two being forbidden. The secondary photoequilibration results in the formation of the latter compounds. Equilibration can also be achieved with an acid catalyst. More vigorous acid treatment, in the absence of water, leads to the formation of a mixture of 4α*H*- (7) and 4β*H*-pyrosantonin (8).

We have also been able to relate the isomer A to

* To simplify the discussion, we employ the same numbering system for the photoproducts as for the starting materials.

[13] F. C. Chang and C. Chiang, *Tetrahedron Letters*, 1969, 891.

[14] M. J. Brienne and J. Jacques, *Tetrahedron*, 1970, **26**, 5087; D. W. Hudson and O. S. Mills, *J.C.S. Chem. Comm.*, 1972, 647.

[15] G. Snatzke in 'Optical Rotatory Dispersion and Circular Dichroism in Organic Chemistry,' ed. G. Snatzke, Heyden, London, 1967, p. 208; J. Levisalles, *ibid.*, p. 306.

[16] R. B. Woodward and R. Hoffman, *Angew. Chem. Internat. Edn.*, 1969, **8**, 781.

isomer C, and D to B. Pyrolysis of dihydro-A (13) at 250° affords dihydro-C (15) as the only product. Similar treatment of dihydro-D (16) affords dihydro-B (14). The isomerisations proceed by cleavage and reformation of the 6,10-bond with inversion at both centres.[17] Neither the 4- nor the 5-position is affected. The driving force in the reaction must be the release of strain in going from a *trans*-fused lactone to a *cis*-fused lactone. Thus if we prove the structures of the *cis*-lactones, the structures of the *trans*-lactones follow.

Evidence which enables us to assign structures (10) and (11) to isomers B and C, respectively, comes from experiments designed to elucidate the mechanism of the photochemical reaction. Photolysis of pyrosantonin (7) is accelerated by triplet sensitisers such as acetophenone (E_T 74 kcal mol^{-1}) (Table 1).[18] The rearrangement should proceed *via* an $n \longrightarrow \pi^*$ or possibly a $\pi \longrightarrow \pi^*$ triplet state.[19] Triplet quenchers, such as naphthalene and piperylene, have no effect, but many examples are known where quenchers are ineffective in triplet-excited reactions.[20] Triplet sensitisers with lower energies than acetophenone are also effective in promoting the photochemical process but the proportions of the various products differ. In these experiments we were only able to obtain the more stable *cis*-lactones quantitatively. The *trans*-lactones, especially if present in small quantities, decomposed on work-up.

TABLE 1

Sensitiser	E_T/ kcal/mol^{-1}	Irradiation time (h)	Yield (mg) of products from 4α*H*-pyrosantonin (250 mg) 4α*H*-Pyrosantonin	Photoproducts A	B	C	D
Acetophenone	74	1	0	105	80	12	†
Phenanthrene	62	8	45	83	73	11	†
2-Acetylnaphthalene	59	3	194	10	*	19	†
		8	98	*	26	17	†
1-Naphthaldehyde	56	8	152	*	0	13	†

* Trace. † Photopyrosantonin D decomposes during work-up.

With acetophenone, the reaction was complete in 1 h, and the principal *cis*-lactone was B. With 2-acetylnaphthalene (E_T 59 kcal mol^{-1}) [18] the reaction was much slower, and the main product at short irradiation times was C. This suggests that the triplet state of acetophenone has enough energy to convert pyrosantonin into the photoproduct C, and also convert the isomer C into B. The triplet state of 2-acetylnaphthalene has enough energy for the former process, but not for the latter. The isomer C must have the structure (11) whose formation from pyrosantonin is symmetry-allowed.

These assignments of structures to B and C are supported by nuclear Overhauser effect (n.O.e.) experiments, and by the n.m.r. spectra themselves. Irradiation at the frequency of the 10-methyl group and examination of the 1-proton signals of B (10) and C(11) shows an 11% increase in intensity in the former case but not in the latter. Models show that the 1-position is 2·9 Å from the 10-methyl in (10) and 4·5 Å in (11). Further the 1-proton in the *trans*-lactone A (9) also shows a significant n.O.e. effect (15%) when the 10-methyl frequency is irradiated.[21]

The 1-proton signal in the n.m.r. spectrum of B is at τ 2·49, *i.e.* at considerably lower field than the corresponding signal in C (τ 2·70). This difference is to be expected, as in B (10) the 1-proton is close to the deshielding 6-oxygen atom of the lactone ring. This is confirmed by the 4-proton signals in B and C. In C (11), the 4-proton is close to the lactone oxygen atom, and the signal is at τ 7·26; in B (10), the 4-proton signal is at τ 7·54. The 4-epimer (21) [11] of (11), in which the 4-proton is not close to the 6-oxygen atom, shows a 4-proton signal at τ 7·38. In the case of the *trans*-fused lactones, the 1-proton signal shown by photopyrosantonin A (9) lies as expected in the same region as that in B (10), but that of D lies even lower still, at τ 2·30. A model of D (using more flexible, and necessarily, less accurate, models than the Dreiding set) suggests that in D the 1-proton comes within the van der Waals radius of the 8β-proton. The 1-proton consequently will be considerably deshielded.[22] This interaction between the 1- and 8-protons may account for the particular instability of this isomer.

There is a possibility that the *cis*-isomers differ in stereochemistry [12] at the 4-position, rather than, or in addition to, the 5-position. Isomerisation at the 4-position could proceed through a photoenolisation reaction.[23] However, we can eliminate this difference in stereochemistry. The photopyrosantonins A—C all show negative $n \longrightarrow \pi^*$ c.d. peaks. The chirality of the enone chromophore, and hence the sign of $n \longrightarrow \pi^*$ peak, will depend on the stereochemistry of the 4-methyl group, which will tend to become 'equatorial.' We may deduce that the 4-methyl stereochemistry is the same in all the lactones. This interpretation is confirmed by the positive $n \longrightarrow \pi^*$ peaks shown by the two photoproducts (21) and (22) of 4β*H*-pyrosantonin.[11] Our results contrast with those of Schaffner and Snatzke,[24] who showed that, in molecules of type (5) with the 4-position unsubstituted, the sign of the $n \longrightarrow \pi^*$ peak in the c.d. spectrum depended on the stereochemistry at the 5-position.

We have already mentioned the hydrolysis and acid treatment of the *trans*-lactones to give the keto-acid (17a). We have followed the pathway of this reaction

[17] R. G. Bergman, *J. Amer. Chem. Soc.*, 1969, **91**, 7405; R. Hoffmann, *ibid.*, 1968, **90**, 1475; *cf.* M. J. Goldstein and M. S. Benzon, *ibid.*, 1972, **94**, 5119.

[18] N. J. Turro, 'Molecular Photochemistry,' Benjamin, New York, 1967, p. 132.

[19] G. March, D. R. Kearns, and M. Fisch, *J. Amer. Chem. Soc.*, 1970, **92**, 2252; G. March, D. R. Kearns, and K. Schaffner, *ibid.*, 1971, **93**, 3129.

[20] *Cf.* H. E. Zimmerman and J. S. Swenton, *J. Amer. Chem. Soc.*, 1964, **86**, 1436.

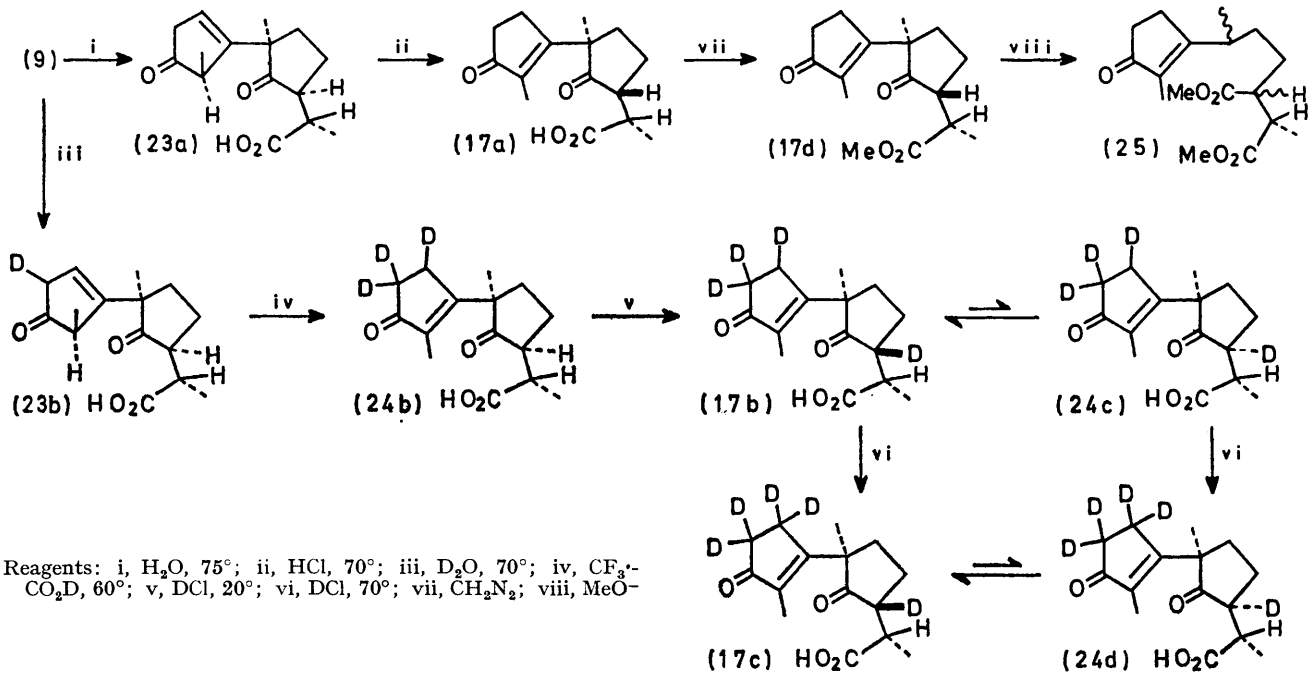
[21] R. A. Bell and J. K. Saunders, *Canad. J. Chem.*, 1970, **48**, 1114.

[22] Ref. 12, p. 71.

[23] *Cf.* D. Bellus, D. R. Kearns, and K. Schaffner, *Helv. Chim. Acta*, 1969, **52**, 971.

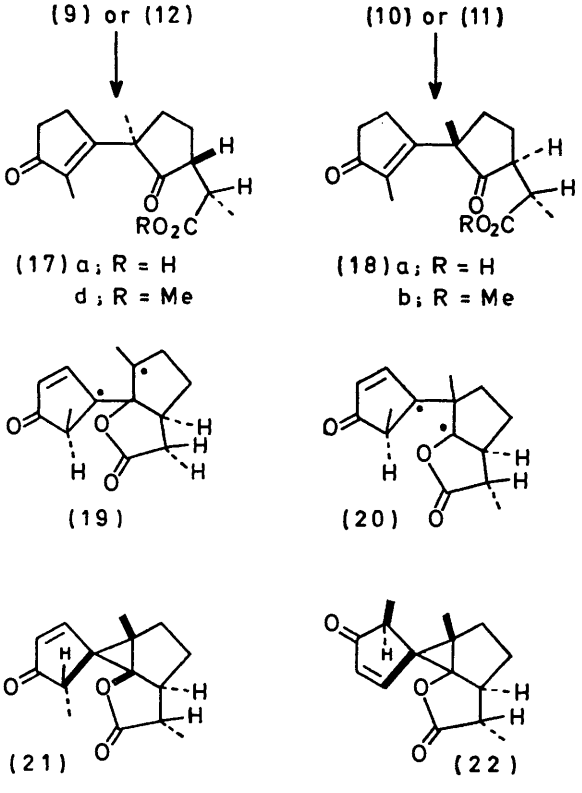
[24] K. Schaffner and G. Snatzke, *Helv. Chim. Acta*, 1965, **48**, 347.

by n.m.r. spectroscopy, carrying out the hydrolysis with water, and (studied in more detail) in deuterium oxide (Scheme). Treatment of compound (9) with water in dioxan at 75°, or with deuterium oxide in deuterioacetone at 70°, affords the βγ-unsaturated ketone (23a) or the 2-deuterio-derivative (23b), respectively. The compounds cannot be isolated, as they are unstable, but the structures follow from the n.m.r. spectra (see Experimental section). Treatment of compound (23a) in dioxan solution with 0·5N-hydrochloric acid affords the αβ-unsaturated ketone (17a) in which we believe the 7-position has isomerised. With deuteriotrifluoroacetic acid, compound (23b) affords the 1,2,2-trideuterio-αβ-unsaturated keto-acid (24b) in which the 7-position is unaffected. Deuteriated hydrochloric acid isomerises this position to give an equilibrium mixture of the 1,2,2,7-tetradeuterio-compounds (24c) and (17b). Further heating replaces the final 1-proton to give a mixture of (24d) and (17c) (see Scheme). The equilibrium between compounds (24) and (17) lies on the side of 7β*H*-isomer (17). This is to be expected as in this isomer the very bulky substituents at the 7- and 10-positions are *trans* to one another.



Reagents: i, H_2O, 75°; ii, HCl, 70°; iii, D_2O, 70°; iv, CF_3·CO_2D, 60°; v, DCl, 20°; vi, DCl, 70°; vii, CH_2N_2; viii, MeO–

SCHEME



Treatment of the methyl ester (17d) with sodium methoxide affords an oily diester, whose structure (25) follows from its n.m.r., i.r., u.v., and mass spectra (see Experimental section).

EXPERIMENTAL

Specific rotations were measured for solutions in chloroform (unless otherwise stated) with a Perkin-Elmer-141 polarimeter. U.v. spectra were measured for solutions in ethanol (unless otherwise stated) with a Unicam SP 800 instrument. I.r. spectra were measured for Nujol mulls with a Perkin-Elmer 157 instrument. N.m.r. spectra for solutions in $CDCl_3$ were measured with a Perkin-Elmer R10 instrument. N.O.e. measurements were carried out with a Hitachi–Perkin-Elmer R20A instrument, with data analyser

attachment. The [$^2H_6$]acetone was degassed. The internal lock-on system and field sweep mode were employed. At least eight measurements were averaged by use of the data analyser. The results must be regarded as qualitative, as a high energy magnetic field (H_2) was required. Mass spectra were measured with a Hitachi–Perkin-Elmer RMS-4 instrument. Photoreactions were carried out under nitrogen with a Pyrex filter, and a Hanovia medium-pressure mercury arc (200 W).

Merck silica gel (0·05—0·20 mm) and fine silica gel (<0·08 mm) were used in column chromatography. For thin-layer plates we used Merck silica gel $HF_{254+366}$ and silica G and for thick-layer plates Merck silica gel $PF_{254+366}$. Light petroleum refers to the fraction of b.p. 40—60°.

and C (11) (100 mg) were eluted in that order. The physical properties are listed in Table 2.

(*b*) 4α*H*-Pyrosantonin (400 mg) in benzene (230 ml) was irradiated as in (*a*). The solvent was removed under reduced pressure, and the residue separated by thick-layer chromatography (20 × 20 cm, ten plates). Two bands were obtained. The upper band gave a mixture of photopyrosantonins A and B (242 mg); from the lower band, a mixture (89 mg) of photopyranosantonins C and D [(11) and (12)] (3 : 10) was obtained. The mixture was used to determine the n.m.r. spectrum of photopyrosantonin D (12) (see also later).

(*c*) 4α*H*-Pyrosantonin (250 mg) and sensitiser (see Table 1) (5 g) in benzene (230 ml) were irradiated as in (*a*). The

TABLE 2

Physical properties of the photolysis products

		A (9)	B (10)	C (11)	D(12)
M.p. (form)		119—120° (leaflets)	153—155° (needles)	163—165° (needles)	
Solvent of cryst.*		Et_2O–P	EtOAc–P	EtOAc–P	
$[\alpha]_D^{22}$ (*c*)		+92° (0·06 in Et_2O)	−79° (0·085 in EtOH)	+120° (0·07 in EtOH)	
Analysis (%) Found [a]	C	73·3	73·2	73·0	
	H	7·2	7·4	7·3	
M+		246	246	246	
$\lambda_{max.}$/nm (log ε)		255(3·68)	255(3·73)	257(3·89)	
$\nu_{max.}$/cm^{-1}		1788 [c]			
		1780	1785	1780	1790 [d]
		1770	1699	1708	1700
		1698	1570	1560	1565
		1577			
c.d.$\lambda_{max.}$/nm(Δε) [e]		331(−2·80)	332(−2·2)	329(−1·70)	
		255(+9·60)	253(+3·53)	259(+17·0)	
τ (*J*/Hz) 4-Me [f]		8·74(8)	8·74(8)	8·70(8)	8·72(8) [g]
11-Me		8·66(7)	8·66(7)	8·70(7)	8·64(7)
10-Me		8·43	8·70	8·59	8·55
4-H [h]		7·49(8)	7·54(8)	7·26(8)	7·39(8)
2-H		3·90(6)	3·85(6)	3·80(6)	3·96(6)
1-H		2·52(6)	2·49(6)	2·70(6)	2·30(6)

* P = Petroleum.

$C_{15}H_{18}O_3$ requires C, 73·2; H, 7·4%; *M*+, 246. [b] In ether. [c] In chloroform, $\nu_{max.}$ 1785 cm^{-1}. [d] Liquid film. Sample from photoequilibration experiment described later, slightly contaminated by acid decomposition products. [e] A in dioxan; B and C in methanol. [f] It was possible to distinguish between the 4- and 11-methyl signals from Eu(dpm)$_3$ studies, also by comparison with the spectra of the corresponding dihydro-derivatives. [g] Measured in a mixture with photopyrosantonin C. [h] The 4-H peaks cannot be detected in the methylene envelopes. Estimated from Eu(dpm)$_3$ studies.

4α- *and* 4β*H-Pyrosantonin* [(7) *and* (8)].—Santonin was pyrolysed as reported previously.[5,10] The neutral mixture (500 mg) was crystallised from diethyl ether (50 ml)–diisopropyl ether (5 ml) to give (by hand picking) 4α*H*-pyrosantonin (290 mg) as plates, m.p. 127—128°, $[\alpha]_D^{24}$ −110° (*c* 0·22), and 4β*H-pyrosantonin* [(11S)-3-*oxo*-4β*H*-*eudesma*-1,5-*dien*-12,6-*olactone*] (150 mg) as rhombs, m.p. 140—142°, $[\alpha]_D^{21}$ −190° (*c* 0·23) (Found: C, 73·6; H, 7·4. $C_{15}H_{18}O_3$ requires C, 73·2; H, 7·4%), *M*+, 246, $\nu_{max.}$ 1795, 1700, 1675, and 1610 cm^{-1}, $\lambda_{max.}$ 336 and 224 nm (log ε 2·16 and 4·06), c.d. (MeOH) 338 and 227 nm (Δε +3·7 and −23·3), τ 8·72 (d, *J* 7 Hz, 11-Me), 8·62 (10-Me), 8·48 (d, *J* 7 Hz, 4-Me), 6·66 (dq, *J* 7 and 2 Hz, 4-H), 4·12 (d, *J* 10 Hz, 2-H), and 3·36 (d, *J* 10 Hz, 1-H).

Photoreaction of 4α*H-Pyrosantonin* (7).—(*a*) 4α*H*-Pyrosantonin (1 g) in dry tetrahydrofuran (230 ml) was irradiated for 4 h; t.l.c. showed four products. The solvent was removed under reduced pressure, and the residue was chromatographed over fine silica gel (300 g) with ether–light petroleum (5 : 5 to 7 : 3) as eluant, under *ca.* 10 mmHg excess pressure of nitrogen. Starting material (116 mg) and photopyrosantonins A (9) (200 mg), B (10) (340 mg), products were rapidly separated by column chromatography on silica (120 g). The yields of products as determined by n.m.r. are recorded in Table 1.

Hydrogenation of the Photopyrosantonins.—(*a*) Photopyrosantonin A (9) (70 mg) and 5% palladium–charcoal (70 mg) in ethyl acetate (50 ml) were stirred in hydrogen for 1 h at room temperature. The catalyst and solvent were removed and the product chromatographed over silica gel to give the dihydro-derivative (13) (55 mg).

(*b*) Photopyrosantonins B (10) (40 mg) and C (11) (32 mg) under the same conditions gave the dihydro-derivatives (14) (25 mg) and (15) (19 mg), respectively.

(*c*) The mixture of photopyrosantonins C and D afforded a mixture of dihydro-derivatives (15) and (16) in the ratio 3 : 7. The physical properties of the dihydro-derivatives are listed in Table 3.

2-[3-*Methyl*-3-(2-*methyl*-3-*oxocyclopent*-1-*enyl*)-2-*oxocyclopentyl*]*propionic Acid* (17a).—(*a*) Photopyrosantonin A (30 mg), dioxan (5 ml), and water (5 ml) were heated at 75° for 1 h. Evaporation left the acid (23a) (t.l.c.), τ 8·95 (d, *J* 7 Hz, 11-Me), 8·75 (d, *J* 8 Hz, 4-Me), 8·72 (10-Me), 7·11 (m, 2-H_2 and 4-H), and 4·07 (m, 1-H), $\nu_{max.}$ 1730, 1700,

and 1620 cm^{-1}. The acid was treated with 2N-hydrochloric acid (5 ml) and dioxan (5 ml) at 70—80° for 1 h. The solvents were removed under reduced pressure and the residue was chromatographed on deactivated silica gel (activity 5) (30 g) with 5% ethanol–chloroform as eluant to give the *diketo-acid* (17a) *hydrate* as needles (from ethyl acetate–light petroleum), m.p. 95—97°, $[\alpha]_D^{21}$ +160° (*c* 0·11 in EtOH) (Found: C, 63·9; H, 8·4. $C_{15}H_{20}O_4,H_2O$ requires C, 63·8; H, 7·9%), M^+, 264, $\nu_{max.}$ 3450, 1730, 1717, 1655, and 1610 cm^{-1}, $\lambda_{max.}$ 243 nm (log ε 4·00), c.d. (MeOH) 314, 306, 243, and 210 nm (Δε +0·55, +0·68, −12·5, and −6·80), τ 8·69 (d, *J* 7 Hz, 11-Me), 8·67 (10-Me), and 8·30 (m, 4-Me).

product was crystallised from ether–light petroleum to give the *ester* (8 mg) as leaflets, m.p. 65—66°, $[\alpha]_D^{21}$ +200° (*c* 0·06 in EtOH) (Found: C, 69·5; H, 8·0. $C_{16}H_{22}O_4$ requires C, 69·0; H, 8·0%), M^+, 278, $\nu_{max.}$ 1725, 1688, and 1622 cm^{-1}, $\lambda_{max.}$ 241 nm (log ε 4·08), τ 8·73 (d, *J* 7 Hz, 11-Me), 8·67 (10-Me), 8·31 (m, 4-Me), and 6·36 (CO_2Me).

TABLE 3

Physical properties of the dihydro-derivatives of the photolysis products

		Dihydro-A (13)	Dihydro-B (14)	Dihydro-C (15)	Dihydro-D (16)
M.p. (form)		143—144° (plates) [a]	142—143° (needles)	154—155° (needles)	
Solvent of cryst.*		Et_2O–P	EtOAc–P	EtOAc–P	
$[\alpha]_D^{23}$ (*c*)		+130° (0·07)	+109° (0·075)	+65° (0·065)	
Analysis (%) Found [b]	C	72·6	72·9	73·0	
	H	8·3	8·2	8·2	
M^+		248	248	248	
$\nu_{max.}/cm^{-1}$		1780	1785	1772	1785 [c]
		1735	1735	1732	1740
τ (*J*/Hz) 4-Me		8·84(8)	8·84(8)	8·83 (8)	8·84(8) [d]
11-Me		8·67(7)	8·71(7)	8·71(7)	8·66(7)
10-Me		8·62	8·77	8·72	8·70

* Petroleum.

[a] A second crystalline form occurs as rhombs, m.p. 151—152°. [b] $C_{15}H_{20}O_3$ requires C, 72·6; H, 8·1%; M^+, 248. [c] Liquid film, obtained in a mixture with dihydro-C (15). [d] Obtained in a mixture with dihydro-C (15).

(*b*) A mixture (3 : 7) of photopyrosantonins C and D (50 mg), water (10 ml), and dioxan (10 ml) were set aside at room temperature for 12 h. The mixture was concentrated and then dissolved in ethyl acetate. The solution was extracted with sodium hydrogen carbonate solution. The extract was acidified and heated to 70° for 1 h, to give the acid (17a) (29 mg) after chromatography, m.p. and mixed m.p. 95—97°. The ethyl acetate layer afforded the lactone (11) (16 mg).

(*c*) For n.m.r. studies, photopyrosantonin A (20 mg) was dissolved in [$^2H_6$]acetone and deuterium oxide and the n.m.r. spectrum was measured, with dioxan as internal standard, τ 8·82 (d, *J* 8 Hz, 4-Me), 8·77 (d, *J* 7 Hz, 11-Me), 8·45 (10-Me), 3·70 (d, *J* 6 Hz, 2-H), and 2·17 (d, *J* 6 Hz, 1-H). The n.m.r. tube was sealed and the mixture heated at 70° for 1 h to give the acid (23b), τ 9·03 (d, *J* 7 Hz, 11-Me), 8·80 (d, *J* 8 Hz, 4-Me), 8·75 (10-Me), and 4·10 (m, 1-H). Deuteriotrifluoroacetic acid (5 drops) was added and the mixture heated to 55—60° for 3 h to give the acid (24b), τ 8·94 (d, *J* 7 Hz, 11-Me), 8·64 (10-Me), and 8·30 (d, *J* 2 Hz, 4-Me). Deuterium chloride in deuterium oxide (20%; 7 drops) was added, and the mixture was set aside overnight. The n.m.r. spectrum showed that the product consisted of the acids (24b) and (17b) (in the ratio 1 : 3), from which the n.m.r. spectrum of (17b) could be identified: τ 8·82 (d, *J* 7 Hz, 11-Me), 8·73 (10-Me), 8·41 (d, *J* 3 Hz, 4-Me), and 7·02 (q, *J* 7 Hz, 11-H). The mixture was heated to 70—80° for 2 h. The 4-methyl signals became broad singlets (τ 8·42 and 8·30), indicating a mixture of acids (24d) and (17c). The mass spectrum of the mixture of methyl esters (see later) of (24d) and (17c) showed M^+, 282 and 283.

The Diketo-ester (17d).—The diketo-acid (17a) (19 mg) was treated with diazomethane in ether. The crude

The Diketo-acid (18a) *and -ester* (18b).—(*a*) Photopyrosantonin B (10) (43 mg), N-hydrochloric acid (5 ml), and dioxan (10 ml) were heated at 80—90° for 1 h. The solvents were removed and the residue was chromatographed on deactivated silica gel (5% ethanol–chloroform as eluant) to give the *diketo-acid* (18a) (40 mg) as needles (from ethyl acetate–light petroleum), m.p. 140—141°, $[\alpha]_D^{22}$ −200° (*c* 0·14 in EtOH) (Found: C, 68·6; H, 7·4. $C_{15}H_{20}O_4$ requires C, 68·2; H, 7·6%), M^+, 264, $\nu_{max.}$ 1736, 1722, 1658, and 1616 cm^{-1}, $\lambda_{max.}$ 294 and 241 nm (log ε 2·39 and 4·03), c.d. (MeOH) 305, 299, 244, and 210 nm (Δε −1·20, −1·06, −11·2, and +6·95), τ 8·82 (d, *J* 7 Hz, 11-Me), 8·72 (10-Me), and 8·29 (m, 4-Me).

(*b*) A solution of the lactone (10) (30 mg) in 0·5N-hydrogen chloride in methanol (10 ml) was refluxed for 2 h, then evaporated under reduced pressure. The residue was purified by thick-layer chromatography to give an oily ester (18b) (27 mg), $\nu_{max.}$ 1732, 1695, and 1625 cm^{-1}, τ 8·87 (d, *J* 7 Hz, 11-Me), 8·74 (10-Me), 8·32 (m, 4-Me), and 6·29 (CO_2Me).

The ester (15 mg), 2N-hydrochloric acid (3 ml), and dioxan (10 ml) were heated at 80—90° for 3 h. The solvents were removed, and the residue was crystallised from ethyl acetate–light petroleum to give the acid (18a) (8 mg), identical with that described in (*a*).

(*c*) Similar treatment of photopyrosantonin C (31 mg) afforded the oily ester (18b) (30 mg) which on hydrolysis afforded the acid (18a), m.p. and mixed m.p. 139—141°, identical with the acid described in (*a*).

Dimethyl 1-*Methyl*-2-[3-(2-*methyl*-3-*oxocyclopent*-1-*enyl*)-*butyl*]*succinate* (25).—A solution of the diketo-ester (17d) (30 mg) in 0·1N-sodium methoxide in methanol (5 ml) was set aside at room temperature for 48 h. The base was neutralised with hydrogen chloride in methanol, and the solvent removed. Extraction of the residue with ether afforded an oil (28 mg) which gave one spot on the t.l.c., M^+, 310 (Calc. for $C_{17}H_{26}O_5$: *M*, 310), $\nu_{max.}$ 1730, 1695, and 1635, $\lambda_{max.}$ 236 nm, τ 8·90br (d, *J* 7 Hz, 11- and 10-Me), 8·31 (m, 4-Me), and 6·32 and 6·28 (two CO_2Me).

Photoequilibration Experiments.—(*a*) Photopyrosantonin A (50 mg) (9) was irradiated in ether (230 ml) for 2 h. The

solvent was removed and the residue chromatographed (thick-layer plates) to afford photopyrosantonins A (22 mg) and D (6 mg), identified by t.l.c. and n.m.r. spectra (ratio of A to D 2 : 1 before work-up).

(*b*) Photopyrosantonin B (50 mg) was irradiated as in (*a*). Thick-layer chromatography separated photopyrosantonin B (38 mg) and C (10 mg) identified by m.p., mixed m.p., and n.m.r. spectra (ratio of B to C 4 : 1, before work-up).

Acid-catalysed Equilibration Experiments.—(*a*) Photopyrosantonin C (11) (28 mg) in deuteriochloroform (0·4 ml) and trifluoroacetic acid (0·1 ml) was heated at 60° for 4 h. The reaction was monitored by n.m.r. spectroscopy. The solvent was removed under reduced pressure and the residue chromatographed (thick-layer) to give photopyrosantonin B (10) (20 mg), m.p. and mixed m.p. 152—153°.

(*b*) Photopyrosantonin B (10) (50 mg) and trifluoroacetic acid (0·5 ml) were heated at 70° for 2 h. Evaporation of the solvent and chromatography of the residue afforded a mixture of 4α*H*-pyrosantonin and 4β*H*-pyrosantonin, m.p. 128—134°, identified by the n.m.r. spectrum of a solution in benzene.

Pyrolysis Experiments.—(*a*) Dihydrophotopyrosantonin A (13) (34 mg) in diphenyl ether (5 ml) was refluxed (252°) for 25 min. The mixture was chromatographed over silica gel (30 g) to give the dihydro-derivative (15) (18 mg) (from ethyl acetate–light petroleum), m.p. and mixed m.p. with authentic sample, 154—155°.

(*b*) The mixture of dihydro-derivatives (15) and (16) (ratio 3 : 7) (25 mg) in diphenyl ether (5 ml) was pyrolysed under the conditions outlined in (*a*). Chromatography of the product afforded the dihydro-derivative (14) (13 mg), m.p. and mixed m.p. 140—142°.

(*c*) Neither dihydro-derivative (14) or (15) was affected under the same conditions.

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