Molecular Orbital and Experimental Studies on the Photoinduced Decarboxylation of Pyrethroid Model Esters

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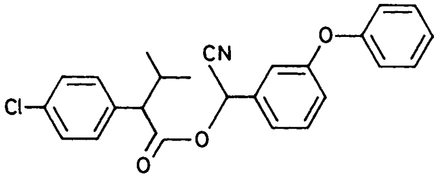
A series of pyrethroid model esters with various substituents in the acid or alcohol moiety have been irradiated by u.v.-radiation ($\lambda > 220$ nm). The main reaction is decarboxylation, as evidenced by gas chromatographic (g.c.) and mass spectrometric (m.s.) analyses. In the photoinduced decarboxylation reaction, the substituent effect on the main transition, which occurs *via* carbonyl excitation, and on the reactivity of a radical intermediate have been examined by semiempirical molecular-orbital calculations (MNDO and CNDO/S). It has been found that the change of benzyl carbon–oxygen bond strength in the excited states is one of the important factors in determining the yield of the decarboxylated product.

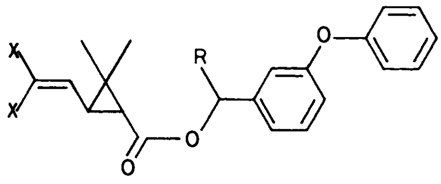
The synthetic pyrethroid insecticides (Figure 1) undergo a variety of photoinduced reactions, such as oxidation, ester cleavage, *cis/trans* isomerization, epimerization in the acid and alcohol moieties, reductive dehalogenation in the acid moiety, and decarboxylation.[1] Of these, ester cleavage, isomerization, and epimerization are the major reactions in the photolysis of newer pyrethroids such as deltamethrin,[2] permethrin,[3] and cypermethrin.[4] In the case of fenvalerate, however, photoinduced decarboxylation occurs, and to a greater extent than with other pyrethroids.[5]

In the photoinduced decarboxylation of various benzyl esters an excited triplet state with subsequent homolytic cleavage between the benzyl carbon and oxygen atom (β-cleavage) seems to be involved.[6] Holmstead *et al.*[7] postulated that the photoinduced decarboxylation of fenvalerate proceeded through homolytic cleavage at the α-cyanobenzyl carbon–oxygen bond followed by loss of carbon dioxide within a solvent cage. Recently, Mikami *et al.*[8] confirmed the processes involved in the formation of the decarboxylated derivative (DEC) by elucidation of the chemical structures of free radical intermediates, using a spin-trap method combined with h.p.l.c., e.s.r., and g.c.–m.s. analyses. However, it has not hitherto been fully understood why the decarboxylation reaction is predominant in fenvalerate photolysis. The following studies were undertaken to find an explanation.

Pyrethroid model esters with various substituents in the acid or alcohol moiety (R^1, R^2, and R^3 in Figure 2) were irradiated in methanol with u.v. radiation ($\lambda > 220$ nm). The resulting photochemical reactions were studied and the effect of substituents on the extent of DEC formation was determined. Further, the effect of substituents on the main transitions that occurred through carbonyl excitation and on the reactivity of a radical intermediate are discussed, based on the results of CNDO/S and MNDO calculations.



fenvalerate



X = Cl, R = H; permethrin
X = Cl, R = CN; cypermethrin
X = Br, R = CN; deltamethrin

Figure 1. The chemical structure of the pyrethroid insecticides.

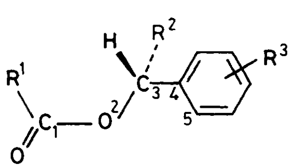
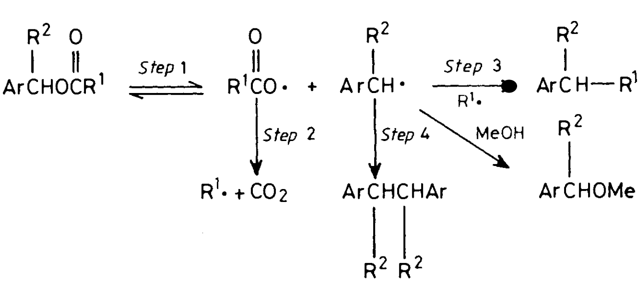


Figure 2. The chemical structure of the pyrethroid model ester.

Results and Discussion

Influence of R^1, R^2, and R^3 Substituents on the Yields of the DEC.—After irradiation of the esters for 2 h, the decarboxylated product (DEC) and other photoproducts, together with starting materials, were recovered from the reaction mixture. The compounds studied and the yields of DEC, expressed as a percentage of starting material ('*Y*'), are listed in Table 1. Previous studies[5,8] indicate that the DEC is formed by homolytic cleavage of the benzyl carbon–alcohol oxygen bond followed by decarboxylation and recombination of the radicals formed (Scheme).

Replacement of the methyl group (R^1) with other alkyl or aromatic groups resulted in an increase in *Y* for compounds (**8**) and (**12**) but a decrease for other compounds (Table 1). The higher *Y*-values for (**8**) and (**12**) are qualitatively explained by the higher stability of allyl and benzyl radicals (produced in steps 1 and 2), as compared with other radicals. The photolysis of compounds (**11**)–(**13**), where R^1 was an aromatic moiety, formed many photoproducts including 1,2-diphenylethane-1,2-dinitrile and α-cyanobenzyl methyl ether derivatives. These photoproducts seem to be formed by dimerization of α-cyanobenzyl radicals and reaction of the α-cyanobenzyl radical with methanol, respectively (step 4).



Scheme. Photoinduced decarboxylation in MeOH (λ > 220 nm), *Step* 1: photoinduced cleavage; *Step* 2: decarboxylation; *Step* 3: recombination; *Step* 4: formation of other photo products.

Table 1. The pyrethroid model esters and the yield of the photoinduced decarboxylation.

Compound	R^1	R^2	R^3	*Y*[a]
(1)	Me	CN	H	33.5
(2)	Me	C≡CH	H	5.3
(3)	Me	H	H	3.5
(4)	Pr	CN	H	23.3
(5)	Pr^i	CN	H	22.6
(6)	Bu^s	CN	H	28.8
(7)	Bu^t	CN	H	20.9
(8)	$CH_2{=}CHCH_2$	CN	H	48.6
(9)	c-Pro[b]	CN	H	10.1
(10)	TMP[c]	CN	H	6.7
(11)	Ph	CN	H	0.0
(12)	$PhCH_2$	CN	H	43.7
(13)	CPI[d]	CN	H	20.8
(14)	Me	CN	3-Cl	28.9
(15)	Me	CN	4-Cl	5.6
(16)	Me	CN	3-F	29.0
(17)	Me	CN	4-F	9.7
(18)	Me	CN	3-Me	28.2
(19)	Me	CN	4-Me	24.1
(20)	Me	CN	3-OMe	36.1
(21)	Me	CN	4-OMe	13.6
(22)	Me	CN	$3-CF_3$	17.0
(23)	Me	CN	$4-CF_3$	2.5
(24)	Me	CN	3-OPh	49.7
(25)	Me	CN	4-OPh	10.6

[a] The yield of decarboxylated compound (% of starting material). [b] Cyclopropyl. [c] 2,2,3,3-Tetramethylcyclopropyl. [d] 1-(4-Chlorophenyl)-2-methylpropan-1-yl.

Table 2. The physicochemical properties of the main transition in the carbonyl excitation and the change of the O(2)–C(3) bond strength (ΔM_{ij}) calculated by CNDO/S.

Compound	λ/nm	OS[a]	Main transition	CI%[b]	ΔM_{ij}
(1)	241.4	0.0006	$\pi \longrightarrow \pi^*$	58.4	−0.9897
(2)	240.0	0.0135	$n \longrightarrow \pi^*$	79.4	+3.067
(3)	243.7	0.0041	$n \longrightarrow \pi^*$	77.3	+6.033

[a] Estimated oscillator strength. [b] Coefficient of CI states.

For compounds (1)–(3), the *Y*-value decreased significantly when the cyano group (R^2) was replaced by the ethynyl group [compound (2)] or a hydrogen atom [(compound (3)]. The major photoproducts were the α-substituted benzyl methyl ethers for (2) (8.7%) and (3) (4.5%). The DEC yield (0%) of compound (11) may be due to the high instability of the phenyl radical formed.

Except for compound (24), the *Y*-value was decreased by substitution in the phenyl ring (R^3). Larger amounts of DEC were formed from α-cyanobenzyl acetate derivatives substituted at the 3-position of the phenyl ring than at the 4-position. In addition to DEC, methyl benzoate and α-cyanobenzyl methyl ether derivatives were identified as photoproducts for compounds (15), (19), and (21) (*ca.* 20%) and for (15), (20), (21), and (24) (<5%), respectively. Since a trace amount of benzoyl cyanide derivative was detected in the photolysis of (15), (19), and (21), the methyl benzoate derivatives would seem to be formed by the reaction of the benzoyl cyanide derivative with methanol.

Structure–Reactivity.—(*a*) *R^2-substituted esters.* The number of photons absorbed or the nature of the transition state species formed by carbonyl excitation affects the *Y*-value. Compounds (1)–(3) showed similar absorption spectra at wavelengths 240–260 nm, and this was attributed to carbonyl excitation. Compound (1) showed an absorption maximum at 248 nm as compared with 255 nm for compounds (2) and (3). The molecular extinction coefficient of (1) was *ca.* three times higher than that of (2) or (3). The number of photons absorbed by (1) was estimated by the Beer–Lambert law to be *ca.* 1.15 times greater than that absorbed by (2) and (3). The *Y*-value of (1) is 6–10 times greater than that of (2) and (3), and this difference would seem to be due mainly to the different main transitions of these compounds.

It is known that both singlet and triplet excited states are (π, π*) in electronic character for the aromatic carboxylic acid derivatives.[9,10] Therefore, CNDO/S calculations were carried out, using the MNDO structures of (1)–(3), to estimate the transitions which occurred by carbonyl excitation. The different main transitions calculated for (1)–(3) are listed in Table 2. The wavelength of a simulated absorption maximum is *ca.* 240 nm for these esters, which agrees quite closely with the experimental data. Furthermore, it was deduced that introduction of a cyano group as R^2 would have caused the (π, π*) character to predominate by carbonyl excitation. It seems that changes in the R^2 moiety can significantly change the character of the transition state formed by carbonyl excitation.

The effect of different R^2 substituents on step 1 was estimated from the change of individual bond strengths (ΔM_{ij}) caused by carbonyl excitation. The ΔM_{ij} of an A–B bond caused by one-electron transition from the molecular orbital *i* to *j* is defined in equation (1). $C_{kp}(A)$ and $C_{kq}(B)$ are the eigenvectors of the

$$\Delta M_{ij} = (M_j - M_i)/2,$$

$$M_k = 2 \sum_{p,q} C_{kp}(A) C_{kq}(B) S_{pq} \quad (k = i,j) \qquad (1)$$

atomic orbitals *p* (on atom A) and *q* (on atom B) in the molecular orbital *k*, respectively. S_{pq} is the overlapping integral between the atomic orbitals *p* and *q*. The negative and positive signs of ΔM_{ij} mean that the A–B bond is weakened and strengthened by a one-electron transition, respectively. The ΔM_{ij} values, listed in Table 2, were negative for the main transition of (1) and positive for those of (2) and (3). These results strongly suggest that the cyano group significantly decreases the O(2)–C(3) bond strength in the excited state, as compared with the ethynyl group and hydrogen atom. Thus, the difference in *Y* seems to arise, at least in part, from the change in the O(2)–C(3) bond strength caused by different transitions.

(*b*) *R^1- or R^3-substituted esters.* There was no significant difference in the optimized structure of the ester linkage or ΔM_{ij} values obtained by CNDO/S calculations among compounds (1) and (4)–(25). These results show that the photo-induced cleavage of the ester linkage (step 1 in the Scheme) should proceed to a similar extent in all of these esters. As the decarboxylation reaction (step 2 in the Scheme) is known to

Table 3. The results of the MNDO calculations for the R^1 radicals derived from the pyrethroid model esters.

Compound	E_D[a]	S_D[b]
(1)	89.8	1.00
(4)	84.0	0.93
(5)	78.0	0.88
(6)	86.2	0.93
(7)	72.2	0.84
(8)	82.4	0.50
(9)	94.4	0.89
(10)	92.1	0.90
(11)	113.8	0.83
(12)	88.9	0.53
(13)	84.2	0.58

[a] Dissociation energy kcal mol^{-1}. [b] Spin density at the radical centre.

proceed very rapidly,[11] the key step that determines the yield of DEC is likely to be the recombination reaction of the radicals formed (step 3). Therefore, the dissociation energy (E_D) and the spin density (S_D) at a radical centre may be considered as the index corresponding to the stability and reactivity of the radicals formed, respectively. The S_D value of each molecule was obtained by MNDO calculation and the E_D value of a radical ($R^{\bullet}$) was estimated from equation (2). In this equation, H_f is the

$$E_D = H_f(R^{\bullet}) + H_f(H^{\bullet}) - H_f(R\text{–}H) \qquad (2)$$

heat of formation (in kcal mol^{-1}) calculated by MNDO. R–H is the protonated derivative formed by combination of the radical ($R^{\bullet}$) with a hydrogen radical ($H^{\bullet}$).

Since MNDO calculations on the R^3-substituted compounds **(14)**–**(25)** afforded an insignificant difference (< 1.0 kcal mol^{-1}) in the E_D value, the relationship between Y and E_D could not be estimated due to the intrinsic error of MNDO. Although the difference in the S_D value was small (*ca.* 0.02 electron), the S_D value of the benzyl carbon C(3) of the radical substituted in the 4-position was slightly lower than that in the 3-position except for compounds **(24)** and **(25)**. This shows that the unpaired electron is more delocalized onto the phenyl π-orbital when the substituent is introduced at the 4-position. This delocalization of the unpaired electron will reduce the degree of recombination of the radicals in a solvent cage, giving more opportunity for the unreacted radical to react with methanol. This possibility is supported by the fact that α-cyanobenzyl methyl ether derivatives are formed as major photoproducts from esters substituted at the 4-position.

In contrast, a greater difference in the E_D value was observed for the R^1-substituted compounds, as listed in Table 3, but the relationship between Y and S_D could not be determined. The lower Y values for the compounds **(9)**–**(11)** are considered to be due to the instability of the radical formed, partly as evidenced by the larger E_D values. For compounds with E_D 70–90 kcal mol^{-1}, the tendency for those pyrethroid model esters with lower E_D values for the R^1 moiety to afford a larger Y value was not clearly demonstrated. This may be due to the greater participation of side reactions such as disproportionation and reaction with methanol than of recombination of the radicals formed. The recovery of photoproducts was low (35–60%) and the volatile photoproducts which were not detected by g.c. analysis under the tested conditions seemed to be formed by these side reactions. In the case of compounds **(12)** and **(13)**, g.c.–m.s. analysis showed that the photoproducts were formed by reaction of the R^1 radicals with methanol.

(*c*) *Synthetic pyrethroids.* Since R^3 = 3-PhO in all the synthetic pyrethroids shown in Figure 1, the difference in the yield of DEC resulting from photolysis depends on the nature of R^1 and R^2. Except for fenvalerate, the acid moieties of these pyrethroids are cyclopropyl derivatives. The photolysis of **(9)**, **(10)**, **(12)**, and **(13)** shows that larger amounts of DEC are produced from the esters possessing benzyl groups in the R^1 moiety. Therefore, it is anticipated that the yield of DEC from fenvalerate would be higher than that from the other pyrethroids. Furthermore, the photolysis of **(1)** and **(3)** shows that the replacement of the cyano group in the R^2 moiety with a hydrogen atom significantly reduces the yield of DEC. Since permethrin possesses a hydrogen atom in the R^2 moiety, it is anticipated that the yield of DEC would be lower than that from the α-cyano pyrethroids shown in Figure 1. From the above, it is likely that the yield of DEC from photolysis of the pyrethroid insecticides shown in Figure 1 decreases in the following order; fenvalerate > deltamethrin = cypermethrin > permethrin. It is known that in the laboratory fenvalerate undergoes photoinduced decarboxylation in high yield.[5,7] In contrast, decarboxylation is of minor importance in the photolysis of deltamethrin[2] and no DEC has been detected in the photolysis of cypermethrin[3] or permethrin.[4] Thus, the estimated order is roughly in agreement with the experimental data. The difference in the yield of DEC between cypermethrin and deltamethrin might be due to the different rate of intersystem crossing which is governed, in part, by a heavy-atom effect.

Calculations

The molecular orbital calculations were executed on each of the steps shown in the Scheme. In step 1, the homolytic cleavage between the acyl carbon C(1) and alcohol oxygen O(2) was ignored because of its minor participation in the photolysis.[5]

The MNDO[12] program loaded on an IBM 370/158MVS computer was used for the theoretical study. The restricted Hartree–Fock operator was used for both of the closed and open shell molecules. The spectroscopic states by excitation were simulated by CNDO/S[13] calculations for the geometries optimized by MNDO calculations. The 60 lowest transitions were taken to consider the configuration interactions (CI).

The initial molecular geometry was derived from the standard values[14] and optimized according to the following rules. The optical isomerism at the benzyl carbon C(3) was defined as the (*S*)-configuration, since the active ingredient of fenvalerate is the (2*S*, α*S*) isomer.[15] The phenyl ring was defined as a planar structure and the following values were used; C–C (1.40 Å), C–H (1.08 Å), and C–C–C, C–C–H (120.0°). The following values were assumed for the halogenated moiety and methyl group; C–F (1.35 Å), C–Cl (1.72 Å), C–C–F (112.0°), C–H (1.10 Å), and C–C–H (109.5°). The other molecular geometries were optimized by an energy-gradient method.

Experimental

Chemicals.—All chemicals, including the various acids, acid chlorides, and benzaldehydes of pure grade, were purchased either from Wako Chemicals Co., Ltd. (Osaka) or from Aldrich Chemical Co. (Milwaukee, Wis.), and used without further purification. The ester derivatives, listed in Table 1, were synthesized from the corresponding cyanohydrin and acid chloride.[7] α-Ethynylbenzyl alcohol, prepared from benzaldehyde and trimethylsilylacetylene by the reported method,[16] was treated with acetyl chloride in order to synthesize **(2)**. The synthesized esters were purified by silica-gel column chromatography (Kieselgel 60, 70–230 mesh; Merck) with chloroform as the eluant and finally by distillation.

The esters synthesized are shown in Table 1, where the positions of the substituents R^1, R^2, R^3 are as shown in Figure 2.

It will be noticed that R^1 in compounds (**10**) and (**13**) are as in fenpropathrin and fenvalerate, respectively.

G.C. Analysis.—The chemical purities of each ester and its photoproducts were determined by g.c. A Shimadzu GC-7A gas chromatograph equipped with a glass column, 1 m × 2 mm i.d., containing 10% SE-30 on Gas-Chrome Q (60–80 mesh) was operated in the programming mode from 70–250 °C at 8 °C min^{-1} with a nitrogen flow rate of 50 cm^3 min^{-1}. A Shimadzu C-ElB recording integrator was used for the quantitative routine analysis.

Spectroscopy.—^{1}H N.m.r. spectra were measured with a Hitachi R-90H Fourier transform n.m.r. instrument in order to characterize each ester. The absorption spectrum of each ester was measured as a dilute solution in MeOH using a Beckman Model DU-50 spectrophotometer with a quartz cuvette (1 cm path length). For the routine analyses, a Hitachi M-80 mass spectrometer, equipped with a Hitachi M-003 data processing unit, was operated in an electron ionization (e.i) mode (20 eV) in combination with g.c. A coiled glass column, 1 m × 2 mm i.d., containing 5% SE-30 on Uniport HP (60–80 mesh) was used in this case. The temperature was varied in a programming mode from 80–250 °C at the rate of 7.5 °C min^{-1} with a helium flow rate of 50 cm^3 min^{-1}.

Photolysis Studies.—The photodegradation studies were carried out by exposing solutions (0.01 mol dm^{-3}) of the test compounds in MeOH to irradiation from a xenon lamp. The test solutions (3 cm^3) were placed in a quartz curvette with a glass cap (Type S17-UV; Gasukuro Kogyo, Inc., Tokyo) at a distance of 45 cm from the light source, at room temperature for a period of 2 h. The light source was a 500 W xenon lamp (Model UXL-5010AA; USIO, Tokyo) equipped with a Toshiba UV-D33S filter ($\lambda > 220$ nm). The resulting solution was analysed directly after irradiation by g.c. and g.c.–m.s.

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