Pyrethroid Photochemistry: Mechanistic Aspects in Reactions of the (Dihalogenovinyl)cyclopropanecarboxylate Substituent

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The reaction quantum yields of six pyrethroid insecticides in methanol at 300 nm vary 3—10-fold between compounds with a cyclopentenone chromophore (allethrin) as compared with the phenoxybenzyl group (*e.g.*, permethrin, decamethrin) in the alcohol moiety. Chlorine confers greater photostability than bromine in pyrethroids with dihalogenovinyl substituents in the acid moiety. Pathways for photodecomposition of methyl [1*R,cis*]-2,2-dimethyl-3-(2,2-dibromovinyl)cyclopanecarboxylate in methanol at 250 or 300 nm involve *cis–trans* isomerization, reductive debromination, and conversion of the dibromovinyl group into a bromomethoxy-epoxide derivative. Isomerization, but not debromination, involves a triplet excited state.

RECENT developments in modifying the structure of natural pyrethrin I (1; R = *cis*-$CH_2CH=CHCH=CH_2$) for enhanced insecticidal potency and photostability have

(1) pyrethrin I (R = *cis*-$CH_2CH=CHCH=CH_2$)
    S-bioallethrin (R = $CH_2CH=CH_2$)

(2) fenothrin (X = Me, Y = H)
    permethrin (X = Cl, Y = H)
    cypermethrin (X = Cl, Y = CN)
    decamethrin (X = Br, Y = CN)

(3) fenvalerate

(4) (X = Cl or Br)

Structures of pyrethrin I, six synthetic pyrethroids, and two methyl 2,2-dimethyl-3-(2,2-dihalogenovinyl)cyclopropanecarboxylates. The isomer examined is shown except as follows: permethrin (1*RS,cis*); cypermethrin (1*RS,cis,αRS*); decamethrin (α*S*); (4; X = Cl) (1*RS,cis*).

led to a new generation of synthetic pyrethroids useful in crop protection.[1] The early synthetic pyrethroids were chrysanthemates [*e.g.* S-bioallethrin (1; R = CH_2CH =

CH_2) and fenothrin (2: X = Me, Y = H) with an easily photo-oxidized isobutenyl substituent.[2] The alternative dihalogenovinyl substituent in permethrin (2; X = Cl, Y = H), cypermethrin (2; X = Cl, Y = CN), and decamethrin (2; X = Br, Y = CN) is resistant to photo-oxidation and is therefore a suitable replacement for enhanced photostability.[1,3] The photolabile chrysanthemate moiety can also be replaced with α-(4-chlorophenyl)isovalerate yielding esters [*e.g.* fenvalerate (3)] which combine high insecticidal activity with adequate stability.[4] No attempt has been made to compare the photo-reactivity of pyrethroids of diverse types under standard conditions.

Our studies on the photodecomposition of permethrin and decamethrin establish two important pathways, reductive dehalogenation and *cis–trans* isomerization at the cyclopropane ring.[5-7] Rate differences are observed between the corresponding dibromo- and dichloro-vinyl compounds,[6] indicating that the acid moiety substituents play an important role in the degradation processes. The dehalogenation reaction in decamethrin may occur *via* free radical or ionic (electron transfer) mechanisms, by analogy with other vinyl bromides for which the multiplicity of the excited state is not established [equation (E1)].[8,9]

cis–trans Isomerization in chrysanthemic acid derivatives is believed to proceed *via* the triplet state of the ester carbonyl.[10,11] The *trans*-isomer is favoured in the photo-stationary state and efficient energy transfer is obtained with various sensitizers.

The present study considers the photo-reactivity of selected pyrethroids and the reactions at 250 and 300 nm of methyl *cis*-2,2-dimethyl-3-(2,2-dihalogenovinyl)-cyclopropanecarboxylates (4; X = Cl or Br) in various solvents.

RESULTS AND DISCUSSION

Photoreactivity of Structurally-related Pyrethroids.—Table 1 compares the reaction quantum yields of six pyrethroids and of (4; X = Cl) and (4; X = Br) at 300 nm in methanol. There is a 3—10-fold difference in reactivity between S-bioallethrin (1; R = $CH_2CH=CH_2$), which contains the strongly-absorbing cyclopentenone

$$X_2C=CH-R \longrightarrow [X \cdots CX=CH-R] \longrightarrow [\overset{-}{X}\overset{+}{C}X=CH-R] \xrightarrow{R'OH} R'OCX=CH-R \qquad (E1)$$
$$\underset{}{\overset{}{\Big\downarrow}} \xrightarrow{R'OH} HCX=CH-R$$

chromophore, and the phenoxybenzyl-substituted compounds. It is evident that a large portion of the light absorbed by the phenoxybenzyl group results in no net reaction since ϕ is greater for the methyl ester (4; X = Br) than for the corresponding pyrethroid (decamethrin). The value of ϕ for cypermethrin can be doubled
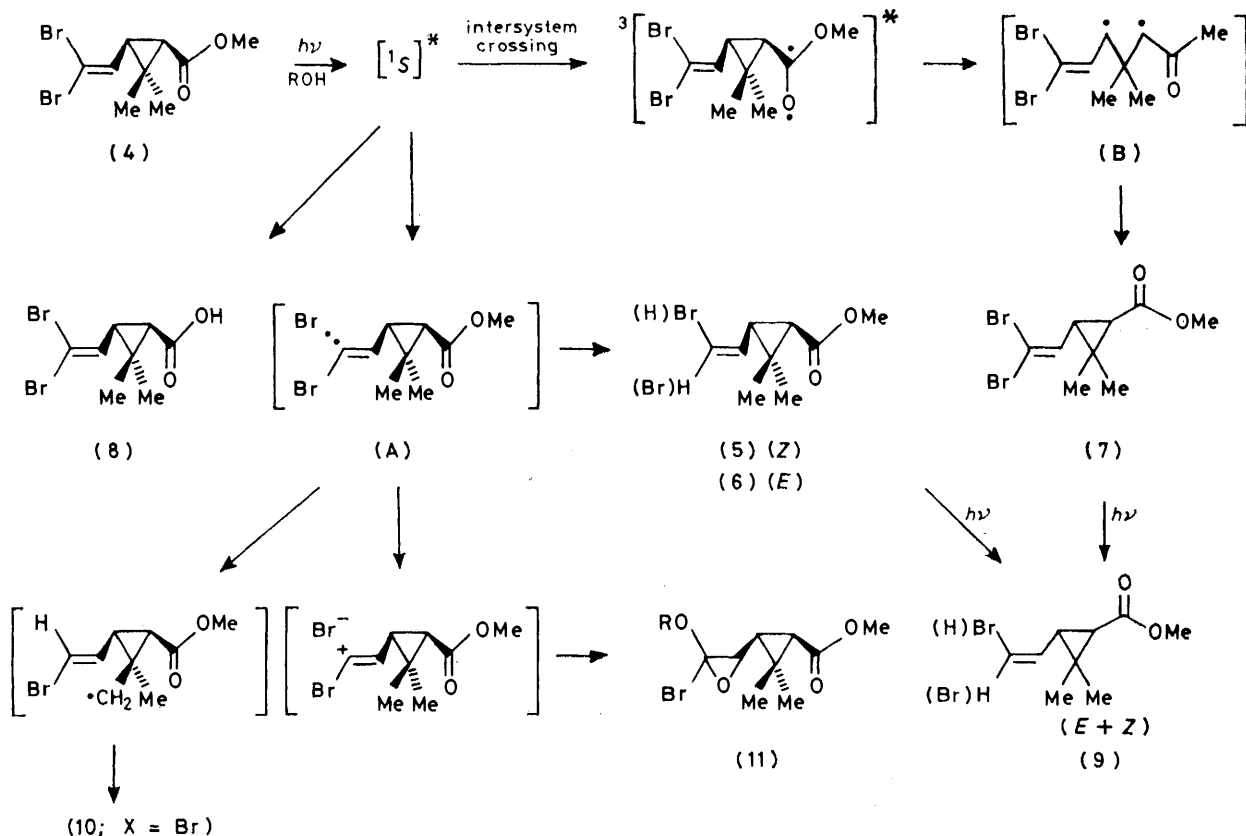
TABLE 1

Reaction quantum yields of pyrethroids and related compounds

Compound	Concentration ($\times 10^{-2}$M)	ϕ_{300}
S-Bioallethrin (1R,trans,4'S) (1; R = CH₂CH=CH₂)	4.3	0.216
Fenothrin (1R,cis) (2; X = Me, Y = H)	5.1	0.070
Permethrin (1RS,cis) (2; X = Cl, Y = H)	1.3	0.018
Cypermethrin (1RS,cis) (2; X = Cl, Y = CN)	3.0	0.022
Decamethrin (1R,cis) (2; X = Br, Y = CN)	2.1	0.043
Fenvalerate (1RS,αRS) (3)	3.4	0.043
(1RS,cis)-(4; X = Cl)	9.0	0.005
(1R,cis)-(4; X = Br)	9.1	0.121

by photolysis in methanol containing 50% 2-bromopropane in a manner analogous to that of (4; X = Cl) as discussed later, suggesting that the photo-stability of

trum (methanol) of (4; X = Cl) exhibits a π–π^* transition (λ_{218}, ε 10 300) similar to that of (4; X = Br) (λ_{222}, ε 12 800). The latter compound, however, shows an additional shoulder band (λ_{263}, ε 580) which may arise by a mixed n–π^*, π–π^* transition, consequently ε_{300} for (4; X = Br) is 10—20 while for (4; X = Cl) it is $ca.$ 0. On changing the solvent to cyclohexane the absorption maximum remains constant, but ε decreases by 5—15% for both compounds. The corresponding α-cyano-3-phenoxybenzyl esters absorb at higher wavelengths and show increased ε values (λ_{210} ε $ca.$ 40 000; λ_{274} ε 2 800). The intensity of these bands allows for considerable absorptivity (ε 50—100) at 300 nm, indicating the importance of the aromatic π–π^* transition in retarding environmental degradation.

Direct Photolysis of (4; X = Cl) *and* (4; X = Br).—At 250 nm in methanol the reaction rate is approximately equal for both compounds in concentrations (0.02—0.04M) at which >95% of the incident light is absorbed. G.l.c. combined with chemical ionization mass spectrometry (c.i.m.s.) reveals that (4; X = Cl) yields 92% of the *E*- and *Z*-isomers of methyl *cis*-2,2-dimethyl-3-(2-chlorovinyl)cyclopropanecarboxylate [(5; X = Cl and (6; X = Cl) in equal amounts], *ca.* 2% of methyl *trans*-2,2-dimethyl-3-(2,2-dichlorovinyl)cyclopropane-

the dihalogenovinyl-substituted pyrethroids is dependent on the nature of the halogen substituent in the acid moiety as well as on the particular alcohol employed.

Ultraviolet Spectroscopy.—The u.v. absorption spec-

carboxylate (7; X = Cl) and <1% of the *cis*-acid (8; X = Cl). Photolysis of (4; X = Br) yields (5; X = Br) (36%), (6; X = Br) (22%) (7; X = Br) (8%), (8; X = Br) (<1%), and 8% of a mixture of the

trans-isomer (9; X = Br) and the unknown (10; X = Br).

Photolysis of (4; X = Cl) at 250 nm in ethanol or propanol yields the same products obtained in methanol but the reaction proceeds *ca.* 50% faster. It therefore appears that hydrogen abstraction from the solvent determines the rate of product formation and that recombination of the chlorine atom–vinyl radical pair occurs to a greater extent in the absence of readily-abstractable hydrogen. The reaction rate is similar for (4; X = Cl) and (4; X = Br), in a way consistent with processes resulting from similar intermediates in which the primary mode of reaction involves bond homolysis. At the wavelength employed more than sufficient energy is available to the excited state for rupture of either C–Br or C–Cl bonds (<85 kcal mol^{-1}). The greater

and (10; X = Br) are not efficiently separated with the dexyl or SE-30 columns used earlier. Under present g.l.c. conditions, (9; X = Br) is partially resolved into two peaks but the ratio of the E and Z isomers could not be determined. Homolysis of a bromine–carbon bond and isomerization occur in an undetermined sequence in formation of (9; X = Br) from (4; X = Br).

An additional monodebromination product (10; X = Br), identical to (5; X = Br), (6; X = Br), and (9; X = Br) in c.i.m.s. characteristics, is formed from (4; X = Br) in methanol and CD$_3$OD. Although poorly resolved from (9; X = Br) by g.l.c. (10; X = Br) is detected under conditions where (9; X = Br) is not likely to form, *i.e.* at low concentrations of (7; X = Br) at early stages of reaction and especially in the presence of piperylene. Photolysis of (7; X = Br) 0.05M in

TABLE 2

Photolysis of methyl [1R,*cis*]-2,2-dimethyl-3-(2,2-dibromovinyl)cyclopropanecarboxylate (4; X = Br) in solution at 300 nm

		Product yield (%) [c]			
Solvent or additive [a]	Percentage reacted [b]	(7; X = Br)	(5; X = Br)	(6; X = Br)	(9; X = Br) + (10; X = Br)
Methanol	21	31	21	16	16
Ethanol	25	32	20	21	8
Propan-2-ol	25	35	22	22	8
Isobutyrophenone (0.41M in methanol) [d]	7	100			
trans-Piperylene (0.07M in methanol)	11	17	28	22	5
CD$_3$OD	20	30	4	2	6
Retention time (min) [e]					
QF-1		9.4	4.0	5.9	5.4
OV-25		8.0	1.8	3.4	3.0

[a] 0.052M (4; X = Br). [b] Irradiation for 1 h with RPR 3000 lamps. [c] Yields are given as percentage of reacted (4; X = Br). [d] The *trans* : *cis* ratio is 2.3 : 1 at the photo-stationary stage. Similar results are obtained with acetone, benzophenone, and naphthalene. [e] Additional values are as follows: (8; X = Br), 10.2 (QF-1) and 9.6 (OV-25); (11; X = Br), 6.6 (OV-25, 80 °C, N$_2$ at 50 ml min^{-1}).

importance of vinyl than of carbonyl excitation at 250 nm is indicated by the finding that isomerization to the *trans*-products, which arise from the latter process, is a minor pathway for both Br- and Cl-substituted compounds.

Irradiation of (4; X = Cl) at 300 nm in methanol results in formation of detectable ($<1\%$) yields of the *trans*-isomer (7; X = Cl) only after very long exposure times [*ca.* $10\times$ that required for 20% conversion of (4; X = Br)]. However, the rate of reaction and of formation of (7; X = Cl) can be increased several-fold by irradiating in the presence of increasing concentrations of n-propyl bromide (10—50%) in methanol. Heavy-atom substitution in the solvent or substrate facilitates singlet–triplet intersystem crossing [12] and thus affects excited state lifetimes and phosphorescence quantum yields.[13]

Photo-reaction of (4; X = Br) at 300 nm proceeds at similar rates in all the solvents studied to give the same products [except (11; X = Br)] but in varying proportions (Table 2). Formation of (5; X = Br) and (6; X = Br) with preference for (5; X = Br) in methanol is analogous to the dehalogenation process observed in decamethrin.[5,6] The E–Z debromination specificity for (4; X = Br) was not previously recognized [6] since (5; X = Br), (6; X = Br), (9; X = Br),

methanol at 300 nm) yields 18% of (4; X = Br), small amounts of (5; X = Br) and (6; X = Br), and 62% of (9; X = Br). Irradiation of either (5 or 6; X = Br), under the same conditions, yields mixtures of (5; X = Br), (6; X = Br), and (9; X = Br). This reaction is quenched efficiently by piperylene, suggesting a triplet process. Since (10; X = Br) does not originate from (5; X = Br), (6; X = Br), or (7; X = Br) other pathways must be considered. Examination of a molecular model of intermediate (A) shows proximity of the *cis*-methyl at C-2 of the cyclopropane to the vinyl radical that gives rise to (6; X = Br). Unknown (10; X = Br) may form by intramolecular H abstraction followed by subsequent reaction of the primary radical, a hypothesis consistent with the greater yield of (5; X = Br) relative to (6; X = Br) in methanol and CD$_3$-OD as shown in Table 2. In ethanol and propan-2-ol, more easily abstractable protons are available and (A) leads only to (5; X = Br) and (6; X = Br). Thus, the yield of (10; X = Br) may be related to the difference in yields of (5; X = Br) and (6; X = Br) *i.e.*, 5% in methanol; (10; X = Br) is possibly a ring-opened compound rather than an isomer of the types (5; X = Br), (6; X = Br) and (9; X = Br).

Bromoalkoxy-epoxide (11; X = Br) is formed in methanol, ethanol, and CD$_3$OD. MeO-(11; X = Br) is

found in *ca.* 5% yield in methanol while its analogues are obtained in lower yields in ethanol and higher yields in CD_3OD. The difference in the yield of (11; X = Br) in methanol and CD_3OD cannot be explained solely on the basis of isotope effects. In any case, accurate quantitation of the products was precluded by their thermal instability on g.l.c. analysis. The ester (4; X = Br) is stable in air and to *m*-chloroperoxybenzoic acid. Although no proof is available for the intermediacy of electron-transfer processes in the formation of (11; X = Br) it is likely that substitution of bromine by solvent occurs prior to epoxidation of the vinyl ether formed. However, the yield is not altered by saturation of the solvent with either N_2 or O_2, indicating that the oxidation may occur during isolation. Compound (11; X = Br) is probably an isomer mixture and it degrades readily yielding many products, only some of which give a positive epoxide test. Photolysis of (4; X = Cl) in methanol at 250 and 300 nm does not yield compounds analogous to (11; X = Br). However, photo-epoxidations are known to occur with other 'deactivated' alkenes, such as tri- and tetra-chloroethylene.[14]

Energy-transfer Reactions of (4; X = Cl *or* Br).—In the isomerization reactions, diradical intermediate (B), arising from carbonyl excitation to the triplet state and cleavage of the C-1–C-3 bond, recombines to give a product mixture in which the *trans* isomer predominates. However, excitation of the ester carbonyl may not be the only route to (7; X = Br) since photolysis of *cis*-2,2-dimethyl-3-(2,2-dibromovinyl)cyclopropylmethanol yields products resulting from both *cis–trans* isomerization and reductive debromination processes.

Studies were carried out with triplet quenchers and sensitizers to determine the multiplicity of the excited states leading to isomerized and debrominated products. On irradiation of (4; X = Cl or Br) at 254 and 300 nm in methanol in the presence of naphthalene (E_t 60.8 kcal mol^{-1}), no reaction was detected with (4; X = Cl) whereas (4; X = Br) yielded (7; X = Br) exclusively. Sensitization by benzophenone, isobutyrophenone, and acetone (E_t 68.5, 73.1, and 78 kcal mol^{-1}, respectively) yielded (7; X = Cl) from (4; X = Cl) and (7; X = Br) from (4; X = Br). Thus, the triplet energy of (4; X = Br) is <60 kcal mol^{-1} and lower than that of (4; X = Cl), in agreement with earlier findings that internal heavy-atom effects include lowered triplet energies.[15] Debrominated products (5; X = Br) and (6; X = Br) in methanol are also sensitized by iso-butyrophenone yielding (9; X = Br). Triplet quenchers such as cyclohexa-1,3-diene (E_t 50.0 kcal mol^{-1}) and *trans*-piperylene (E_t 53.0 kcal mol^{-1}) reduce the reaction rate of (4; X = Br) and the yield of (7; X = Br) and (9; X = Br). It therefore appears that the isomerization process, but not debromination, involves a triplet excited state.

EXPERIMENTAL

Sources or Synthesis of Compounds. Decamethrin and *S*-bioallethrin were gifts from Roussel-Uclaf (Paris, France),

cis-permethrin and the *cis*- and *trans*-isomers of (8; X = Cl) from FMC Corp. (Middleport, N.Y., U.S.A.), fenothrin and fenvalerate from Sumitomo Chemical Co. (Osaka, Japan), and cypermethrin from Shell Research Ltd. (Sittingbourne, Kent, U.K.). Sensitizers and quenchers were from Aldrich Chemical Co. (Milwaukee, Wis., U.S.A.). Compounds (4; X = Br)—(8; X = Br) and *cis*-2,2-dimethyl-3-(2,2-dibromovinyl)cyclopropylmethanol were obtained and characterized as previously described.[6] Analogous procedures were used to prepare (4; X = Cl) and (7; X = Cl) from *cis*- and *trans*-(8; X = Cl). Compound (9; X = Br) was prepared by reaction of (7; X = Br) (1.6 mmol) with triphenyltin hydride (5 mmol) in benzene (5 ml) on irradiation at 300 nm; it was characterized by its $[M + 1]^+$ cluster at 233 (c.i.m.s.).

Spectroscopy.—N.m.r. spectra were obtained in $CDCl_3$ containing 1% tetramethylsilane as internal standard using a Perkin-Elmer R32B 90-MHz spectrometer equipped with a Nicolet Model 1080 Fourier-transform computer. C.i.m.s. utilized the following system: Finnigan Model 1015D spectrometer; System Industries Model 150 computer; when coupled for g.l.c., the Finnigan Model 9500 gas chromatograph with a column of 5% OV-17 on Chromosorb W (80—100 mesh) operated with temperature programming (80—140 °C, 4 °C min^{-1}) using He as carrier gas (20 ml min^{-1}). Isobutane was the reagent gas with a c.i. source pressure of 0.3—0.5 Torr at 70 eV.

Chromatography and Analyses. G.l.c. for quantitation utilized a Varian Aerograph Series 1400 instrument equipped with a flame-ionization detector and the following glass columns (2 m × 3 mm i.d.): 3% QF-1 or 5% OV-25 on Chromosorb W (80—100 mesh); 3% Dexil on Varaport 30 (80—100 mesh). Column temperatures were as follows: QF-1 and OV-25, 80—140 °C, 4 °C min^{-1}; Dexil, 200—300 °C, 10 °C min^{-1}. N_2 was the carrier gas at 30 ml min^{-1}. Individual peak areas were compared with those of the corresponding authentic standards or, when standards were not available, with those of related compounds with similar retention times.

T.l.c. utilized silica gel 60 F-254 chromatoplates (0.25 mm) for analytical studies and silica gel GF chromatoplates (1 mm) for preparative isolations. The solvent systems were: A, carbon tetrachloride–ether (3 : 1); B, hexane–ether (1 : 1), two developments. Products were routinely detected by their quenching of gel fluorescence at 254 nm or by spraying with 20% (w/v) phosphomolybdic acid in ethanol followed by heating at 100 °C for 5 min. Epoxides were detected with 4-(*p*-nitrobenzyl)pyridine reagent.[16]

Irradiation Procedures.—Samples (1 ml) in spectroscopic quality solvents were held in a 'merry-go-round' arrangement and photolysed (1—4 h) in a Rayonet reactor (The Southern N.E. Ultraviolet Co., Middletown, Conn., U.S.A.) equipped with RPR 2537 or RPR 3000 lamps, using quartz or borosilicate tubes, respectively. Actinometry was based on the triplet reaction of cyclopentanone to pent-4-enal ($\phi = 0.37$, 313 nm).[17]

Characterization of Photo-products.—Photo-products (5—8; X = Cl) and (5—9; X = Br) were identified by g.l.c. co-chromatography with authentic standards using OV-25 and QF-1 columns (Table 2) and by g.l.c.–c.i.m.s.

MeO-(11; X = Br) was isolated by preparative t.l.c. (R_F: A 0.43, B 0.41) of the reaction mixture obtained by irradiation of (4; X = Br) (0.01M) in methanol (300 nm). It decomposes above 70—80 °C by g.l.c. (OV-25) analysis. C.i.m.s. (direct probe) reveals the $[M + 1]^+$ cluster at

m/e 279 (40%), 280 (5%), 281 (45%), and 282 (5%) as characteristic for monobromo-substitution. N.m.r. spectroscopy shows signals at δ 1.22—1.29 (m, 6 H), 1.58—2.04 (m, 2 H), 3.22 (s, 1 H), and 3.64—3.77 (m, 6 H). The singlet at δ 3.22 is assigned to the epoxide proton, although a doublet is expected. However, molecular models reveal the likelihood of an unfavourable angle (80—100°) for coupling between this proton and that at C-3 of the cyclopropane, resulting in a very low coupling constant.[18] The i.r. spectrum of MeO-(11; X = Br) in chloroform shows ν(C=O) at 1 735 cm^{-1}. Analogues of (11; X = Br) obtained in ethanol and CD$_3$OD give the corresponding c.i.m.s. signals (direct probe) for $[M + 1]^+$ at m/e 293 and 282, respectively. These analogues also give a positive epoxide colour test.

Four photo-products of *cis*-2,2-dimethyl-3-(2,2-dibromo-vinyl)cyclopropylmethanol were tentatively identified by treatment of the reaction mixture with KMnO$_4$ followed by methylation (CH$_2$N$_2$) to give as major derivatives (5; X = Br), (6; X = Br), (7; X = Br), and (9; X = Br).

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