# A Quantitative Investigation of the Ozonolysis Reaction. VIII.[1] On the Direction of Cleavage of Primary Ozonides of Selected Unsymmetrical Olefins

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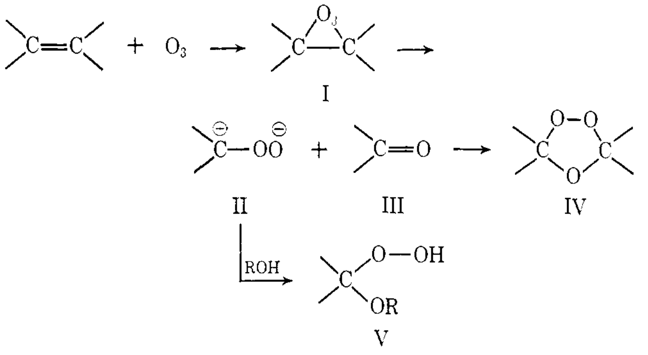
**Abstract:** The cleavage of the primary ozonides of a series of unsymmetrical olefins, $R_1C_6H_4CH{=}CHR_2$, has been studied. The proportions of the two ways of cleavage to yield (a) $R_1C_6H_4CHO + R_2C^+HOO^-$ and (b) $R_1C_6H_4C^+HOO^- + R_2CHO$ have been found to be related to Hammett's $\sigma$ and $\rho$ constants by the equation $\log [x/(1-x)] = -\Delta\Delta G_0^{\ddagger}/2.3RT + (\rho_a - \rho_b)\sigma$, providing the compounds involved have a common $R_2$ substituent ($x$ = proportion of cleavage following route a; $\Delta\Delta G_0^{\ddagger}$ = Gibbs activation energy difference between assumed transition states of the primary ozonide, when $R_1$ = H). An interpretation of the Hammett relationship and of the behavior of the $R_2$ groups in terms of transition states concludes that the zwitterion, which is formed preferentially, is the one whose environment is better able to stabilize the positive charge by increasing the electron density in the vicinity of the potential zwitterionic carbocation (in the transition state) *via* inductive and mesomeric effects. The relative efficiencies of the $R_2$ groups in stabilizing zwitterions can be placed in the order $COCH_3 > CH_3 > COOH > Ph > H > CH_2OH > COOCH_3$. The behavior of the groups $COCH_3$ and COOH, which tend to stabilize the zwitterions $R_2C^+HOO^-$ despite the fact that they are electron-withdrawing groups, is explained by resonance stabilization.

The mechanism of ozonolysis proposed by Criegee[2] has been the object of several recent studies. This mechanism is outlined in Scheme I.

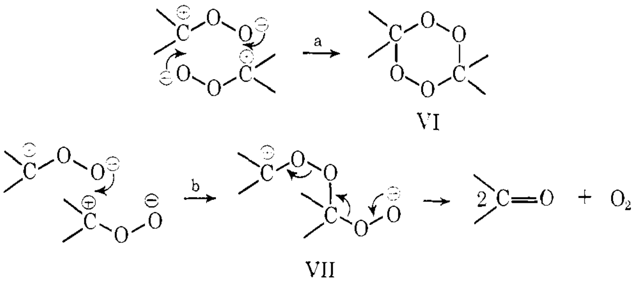
**Scheme I**



The attack of ozone on the C=C double bond yields a primary ozonide I, which cleaves to give a zwitterion II and a carbonyl compound III (aldehyde or ketone). In the absence of a reagent (an alcohol or acid, for example) which would react with the zwitterion II to form a hydroperoxide V, the zwitterion can react with the carbonyl compound III to give the ozonide IV, or, alternatively, polymerize to give peroxides. Excluding those cases in which the carbonyl function is activated[3] ($\alpha$-ketonic esters, for example) or is situated in the same molecule as the zwitterionic moiety,[4] II and III will not react to give the ozonide IV, if III is a ketone[5] since the ketonic carbonyl group is less susceptible to a nucleophilic attack than is the aldehydic carbonyl group.

The reactions between zwitterions are known[6] to yield dimeric peroxides[7] VI (reaction a) and also to follow the reaction path b, which leads to the formation of open-chain peroxides[8] VII (Scheme II). For a series of symmetrical olefins,[8b] it has been shown that approximately 44% of the zwitterion which is not involved in ozonide formation yields open-chain peroxides. These peroxides, when formed of $RC^+HOO^-$ units, decompose rapidly at room temperature into aldehyde and $O_2$,[8b,9] whereas such polymeric peroxides are relatively stable at 25° in $CCl_4$ when they are composed of ketonic carbonyl oxides.[8]

**Scheme II**



Although many observations have been explained satisfactorily by Criegee's mechanism,[6] there are several observations which cannot (at least at first sight) be readily explained by this mechanism. The first inconsistancies arose from the experimental finding[10] that *cis* and *trans* isomers of 1-arylpropenes did not give the same proportions of products (ozonides, aldehydes, and peroxides). The subsequent observations[1,11] that the

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[1] Part VII: S. Fliszár and J. Carles, *J. Am. Chem. Soc.*, **91**, 2637 (1969).

[2] R. Criegee and G. Wenner, *Ann.*, **564**, 9 (1949); R. Criegee, *ibid.*, **583**, 1 (1953); R. Criegee, *Record Chem. Progr.*, **18**, 111 (1957).

[3] R. Criegee, Advances in Chemistry Series, No. 21, American Chemical Society, Washington, D. C., 1958, p 133; R. Criegee, S. S. Bath, and B. V. Bornhaupt, *Chem. Ber.*, **93**, 2891 (1960).

[4] R. Criegee and G. Lohaus, *ibid.*, **86**, 1 (1953).

[5] The reaction of aldehydic zwitterions with acetone, used as a solvent, has been observed: R. W. Murray, P. R. Story, and L. D. Loan, *J. Am. Chem. Soc.*, **87**, 3025 (1965).

[6] *Cf.* P. S. Bailey, *Chem. Rev.*, **58**, 926 (1958).

[7] In some cases, as in the ozonization of tetramethylethylene, higher polymeric peroxides are observed: R. Criegee and G. Lohaus, *Ann.*, **583**, 6 (1953).

[8] (a) S. Fliszár, D. Gravel, and E. Cavalieri, *Can. J. Chem.*, **44**, 67 (1966); (b) S. Fliszár and J. B. Chylińska, *ibid.*, **46**, 783 (1968).

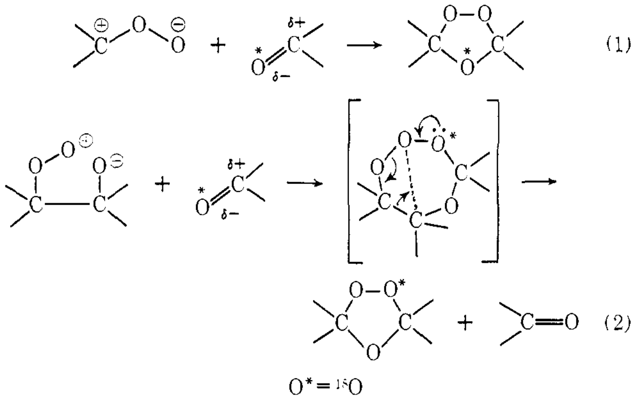
[9] S. Fliszár, D. Gravel, and E. Cavalieri, *ibid.*, **44**, 1013 (1966); S. Fliszár and J. B. Chylińska, *ibid.*, **45**, 29 (1967).

[10] E. Briner, E. Dallwigk, and M. Ricca, *Helv. Chim. Acta*, **41**, 1390 (1958); E. Briner and M. Ricca, *ibid.*, **41**, 2178 (1958); E. Briner and S. Fliszár, *ibid.*, **42**, 1310 (1959); E. Briner and S. Fliszár, *ibid.*, **42**, 2063 (1959).

*cis-/trans*-ozonide ratios for the normal ozonides, as well as for the cross ozonides obtained from unsymmetrical olefins, depend on the olefin geometry, induced several workers to offer alternative explanations for the mechanism of ozonide formation.

The explanation for the stereospecifical dependance of the ozonide *cis/trans* ratio on the geometry of the olefin suggested by Story, Murray, and Youssefyeh[12] is concerned with the *trans*-disubstituted and relatively unhindered *cis*-disubstituted olefins. However, for the class of olefins studied in this paper, *i.e.*, ethylenes containing at least one phenyl group, this theory has been found to be inadequate.[13] As recently shown,[1,15] the MSY mechanism may be readily distinguished from Criegee's mechanism by ozonolyses in the presence of $^{18}$O-labeled aldehyde, and noting the position of incorporation of the $^{18}$O (Scheme III, eq 1 is Criegee's mechanism; eq 2 is the mechanism of MSY).

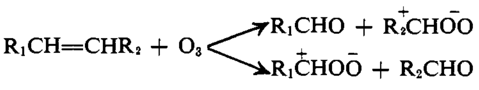
**Scheme III**



The ozonization of *cis*- and *trans*-stilbene, styrene, *trans*-$\beta$-methylstyrene, and triphenylethylene in the presence of $^{18}$O-labeled benzaldehyde reveals that the incorporation of the $^{18}$O takes place exclusively in the ether oxygen of the ozonides formed.[1,15] This is predicted on the basis of the Criegee mechanism. The stilbene ozonide *cis/trans* distributions obtained from these olefins depend on the geometry of the particular olefin, but the presence of excess benzaldehyde does not affect the *cis/trans* distributions.[1] It is therefore unlikely that a primary ozonide–aldehyde reaction is involved. A refined Criegee mechanism (*e.g.*, in terms of *syn*- and *anti*-zwitterions, as proposed by Criegee[16] and recently developed by Bailey[17]) is consistent both with the observations of the labeling experiments and the stereospecificity of the *cis*- and *trans*-ozonide formations. It is therefore proposed to adopt Criegee's mechanism for the subsequent discussion of the ozonolyses presented here.

Despite the detailed study into the ozonolysis reaction, a significant factor has been largely overlooked. This is the direction of cleavage of unsymmetrical olefins, which, assuming Criegee's mechanism, can be represented by Scheme IV.

**Scheme IV**

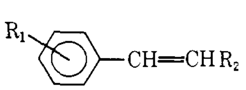


$$R_1CH{=}CHR_2 + O_3 \begin{cases} \rightarrow R_1CHO + R_2\overset{+}{C}HO\overset{-}{O} \\ \rightarrow R_1\overset{+}{C}HO\overset{-}{O} + R_2CHO \end{cases}$$

Recent studies with indene[18] and styrene[19,20] tend to show that the electronic effects invoked for the prediction of the relative importance of the two modes of cleavage are often overestimated. The two ways of cleavage predicted by Criegee's theory for the ozonolysis of indene are of roughly equal importance and, for styrene, the cleavage of the primary ozonide to give PhCHO + $HC^+HOO^-$ occurs to the extent of 41 ± 1%.

In many cases[6] the zwitterion which has the better possibility of resonance stabilization seems to be formed preferentially. However, the electron-donating power of the substituents may participate,[6,20] with the result that one cleavage path is favored. Bailey's[21] experiments on 1,2-dibenzoyl-1-methoxyethylene, which showed that the cleavage to give $PhCOC^+HOO^-$ + $PhCO(CH_3O)C{=}O$ occurs to approximately 75–85%, indicate that the inductive effects, rather than the resonance effect of the methoxyl group, governed the course of the reaction. These views are confirmed by the determination of the relative importance of the two ways of cleavage of a series of ring-substituted styrenes[20] in which the electron-donating substituents favor the formation of $ArC^+HOO^-$ + HCHO. Similarly, Keaveney, *et al.*,[22] conclude on basis of determinations of the direction of cleavage of the primary ozonides of styrene, $\beta$-methylstyrene, and 2-methylpropenylbenzene, that polarization due to the combined inductive effects of the substituents controlled the direction of cleavage; the resonance factors seem to play a negligible part in the cleavage of these primary ozonides.

It is considered that the electronic effects governing the relative proportions of cleavage of primary ozonides into zwitterion and carbonyl compound require further examination. These proportions have been studied for a number of olefins of the type



with $R_1$ = $p$-$CH_3O$, 3,4-$CH_2O_2$, $p$-$CH_3$, H, $p$-Cl, $m$-Cl, $m$-$NO_2$, and $p$-$NO_2$ and $R_2$ = $COOCH_3$, $CH_2OH$, H, $C_6H_5$, COOH, $CH_3$, and $COCH_3$. All the 1,2-disubstituted ethylenes had *trans* configuration.

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(11) G. Schröder, *Chem. Ber.*, **95**, 733 (1962); P. Kolsaker, *Acta Chem. Scand.*, **19**, 223 (1965); O. Lorenz and C. R. Parks, *J. Org. Chem.*, **30**, 1976 (1965); F. L. Greenwood and B. J. Haske, *Tetrahedron Letters*, 631 (1965); R. W. Murray, R. D. Youssefyeh, and P. R. Story, *J. Am. Chem. Soc.*, **88**, 3143 (1966); F. L. Greenwood, *ibid.*, **88**, 3146 (1966); R. W. Murray, R. D. Youssefyeh, and P. R. Story, *ibid.*, **89**, 2429 (1967).

(12) P. R. Story, R. W. Murray, and R. D. Youssefyeh, *ibid.*, **88**, 3144 (1966); R. W. Murray, R. D. Youssefyeh, and P. R. Story, *ibid.*, **89**, 2429 (1967).

(13) For *trans*-1,2-diisopropylethylene, however, ozonized in the presence of acetaldehyde-$^{18}$O, Story, *et al.*,[14] reported a substantial $^{18}$O incorporation in the peroxidic oxygen of the resulting ozonide.

(14) P. R. Story, C. E. Bishop, J. R. Burgess, R. W. Murray, and R. D. Youssefyeh, *J. Am. Chem. Soc.*, **90**, 1907 (1968).

(15) S. Fliszár, J. Carles, and J. Renard, *ibid.*, **90**, 1364 (1968).

(16) R. Criegee in "Peroxide Reaction Mechanisms," J. O. Edwards, Ed., Interscience Publishers, Inc., New York, N. Y., 1962, p 29.

(17) N. L. Bauld, J. A. Thompson, C. E. Hudson, and P. S. Bailey, *J. Am. Chem. Soc.*, **90**, 1822 (1968).

(18) S. Fliszár, Cz. Bel'ecki, and J. B. Chylińska, *Can. J. Chem.*, **45**, 221 (1967).

(19) S. Fliszár, *ibid.*, **44**, 2351 (1966).

(20) S. Fliszár, *Tetrahedron Letters*, 6083 (1966); S. Fliszár and J. Renard, *Can. J. Chem.*, **45**, 533 (1967).

(21) P. S. Bailey, S. B. Mainthia, and C. J. Abshire, *J. Am. Chem. Soc.*, **82**, 6136 (1960).

(22) W. P. Keaveney, M. G. Berger, and J. J. Pappas, *J. Org. Chem.*, **32**, 1537 (1967).

## Results

The ozonolysis of unsymmetrical olefins in an inert solvent produces two carbonyl compounds and two zwitterions (Scheme IV). The reactions between these zwitterions and the carbonyl compounds (if these are aldehydes) will thus yield three ozonides: the "normal" ozonide, corresponding to the initial olefin, and two cross ozonides. In addition certain amounts of carbonyl compound will remain unreacted, due to the reaction between zwitterions to form peroxides, and some aldehyde will be produced by the reduction of zwitterions (Scheme II) with elimination of $O_2$. Because of the complexity of these reactions, it appears that the ozonolysis of unsymmetrical olefins in an inert solvent is unsuitable in view of the determination of the relative importance of the two possible ways of cleavage.

However, when the ozonolyses are performed in the presence of methanol,[23] the zwitterions $R_1C^+HOO^-$ and $R_2C^+HOO^-$ will react to give the corresponding methoxyhydroperoxides $R_1CH(OCH_3)OOH$ and $R_2CH(OCH_3)OOH$, which are sufficiently stable to permit their titration by iodometric methods, and do not react further with the carbonyl compounds formed during the ozonolysis. The trapping of the zwitterions by the added methanol is sufficiently rapid to prevent their reduction to carbonyl compounds (Scheme II). Table I confirms that, with some olefins, 1 mol of hydroperoxide is formed during the ozonization of 1 mol of olefin.

**Table I.** Amounts of Olefin Used and of Hydroperoxides Formed in the Ozonolysis of Some Olefins, at 25°

| Olefin | Initial concn, $M$ | Olefin used, mmol | Hydroperoxide formed, mmol |
|---|---|---|---|
| Tetraphenylethylene | 0.05 | 0.23 | 0.24 |
| | | 0.60 | 0.61 |
| Stilbene | 0.10 | 0.51 | 0.52 |
| | | 1.83 | 1.82 |
| Styrene | 0.20 | 0.96 | 0.96 |
| | | 1.40 | 1.39 |
| Cinnamyl alcohol | 0.10 | 0.47 | 0.46 |
| | | 0.81 | 0.83 |
| *trans*-β-Methylstyrene | 0.10 | 0.64 | 0.64 |
| | | 1.14 | 1.12 |

It has been shown previously[20] that, in the case of some 4,4′-disubstituted stilbenes, of the stilbene, and of tetraphenylethylene,[8a] equal amounts of carbonyl compound and hydroperoxide are formed upon ozonolysis in the presence of methanol. Therefore, assuming Criegee's stoichiometry and that the trapping of the zwitterions by methanol is quantitative, if the methoxyhydroperoxides do not react with the carbonyl compounds,[26] the total amount of the aldehyde formed in each case equals the amount of olefin used. This is illustrated by some examples in Table II.

**Table II.** Ozonization of 1 mmol of $C_6H_5CH{=}CHC_6H_4R$ in $CCl_4$ Solution, Containing 1.0 $M$ $CH_3OH$, at 25°

| R | Initial concn of olefin, $M$ | Aldehydes formed, mmol $RC_6H_4CHO$ | Aldehydes formed, mmol $C_6H_5CHO$ | Olefin used, mmol |
|---|---|---|---|---|
| *p*-$CH_3$ | 0.05 | 0.165 | 0.260 | 0.422 |
| | | 0.196 | 0.274 | 0.472 |
| | | 0.181 | 0.324 | 0.504 |
| | | 0.238 | 0.390 | 0.632 |
| -Cl | 0.05 | 0.286 | 0.160 | 0.446 |
| | | 0.366 | 0.200 | 0.566 |
| | | 0.375 | 0.210 | 0.584 |
| | | 0.383 | 0.212 | 0.590 |
| *p*-$NO_2$ | 0.015 | 0.290 | 0.041 | 0.322 |
| | | 0.318 | 0.041 | 0.342 |
| | | 0.587 | 0.057 | 0.581 |
| | | 0.635 | 0.064 | 0.673 |

In Table III the results of the ozonization of triphenylethylene in $CCl_4$ and in the presence of 1.0 $M$ $CH_3OH$ are given. These results confirm the reliability of the mass balance that will be used to determine the relative proportions of the two ways of cleavage, *i.e.*, 1 mol of olefin on ozonolysis yields 1 mol of the hydroperoxide mixture and 1 mol of the carbonyl compound mixture. Inspection of these data shows that there are no regular trends in the experimental errors. From the values given in Table III it can be calculated that 1 mol of triphenylethylene yields an average of 0.71 mol of PhCHO and 0.29 mol of $Ph_2C{=}O$. Hence the cleavage of this olefin is found to proceed as shown in Scheme V.

**Table III.** Ozonization of Triphenylethylene in $CCl_4$, in the Presence of 1.0 $M$ of $CH_3OH$, at 20°

| Reacted olefin, mmol | Products formed, mmol Hydroperoxide | $Ph_2CO$ | PhCHO | Proportion of cleavage giving PhCHO |
|---|---|---|---|---|
| 0.19 | 0.195 | 0.053 | 0.13 | 0.710 |
| 0.34 | 0.33 | 0.09 | 0.23 | 0.718 |
| 0.36 | 0.37 | 0.11 | 0.27 | 0.710 |
| 0.39 | 0.37 | 0.11 | 0.26 | 0.702 |
| 0.47 | 0.44 | 0.13 | 0.33 | 0.717 |

As explained in the Experimental Section, in certain cases it was not possible to measure the amounts of both of the carbonyl compounds formed. However, it is

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(23) It is considered, in agreement with the Criegee mechanism, that the methanol does not influence the cleavage of the primary ozonide at the temperature (20–25°) at which most of the present experiments have been performed. The primary ozonide of *trans*-di-*t*-butylethylene which, at −78°, is particularly "stable" compared to other primary ozonides, decomposes explosively[24] when "heated" to −60°. It seems reasonable, therefore, to assume that, at 25°, the highly exothermic decomposition of the primary ozonides of substituted phenylethylenes, which are probably less stable, precedes any possible interaction with methanol. This hypothesis is confirmed (i) by the observation that the proportions of cleavage are not affected by change in the temperature of ozonolysis and (ii) by the results obtained using different solvents, including pure methanol and ethanol, which show that the solvent and the alcohol concentration do not affect the direction of cleavage.[25]

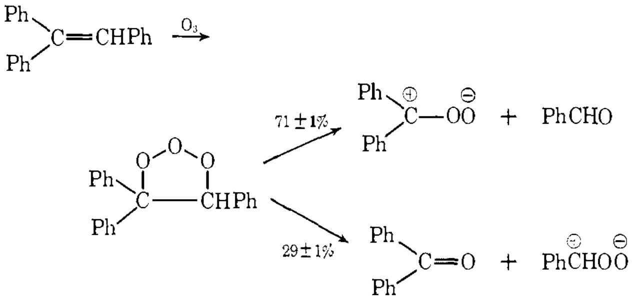
(24) R. Criegee and G. Schröder, *Chem. Ber.*, 93, 689 (1960).

(25) S. Fliszár, and J. Renard, to be published shortly.

(26) Bailey, *et al.*,[27] have shown that methoxyhydroperoxides react with aldehydes in Baeyer–Villiger fashion when the reaction mixtures are allowed to stand for several days at room temperature, and when they are heated to reflux until the peroxide is decomposed. It is important, therefore, to analyze for aldehyde immediately. However, control analyses performed 2 hr after the ozonolysis did not indicate any appreciable change in the aldehyde content. Following a suggestion by Professor P. S. Bailey, dimethyl fumarate was ozonized in methanol at room temperature, and an equivalent amount of benzaldehyde added. Analyses performed immediately, and 1 hr after the reaction, demonstrated unambiguously that no aldehyde reacted with the hydroperoxide. These analyses were performed by gas chromatography, as indicated in the Experimental Section. These control experiments thus confirm the results given in Tables *II* and *III*, which indicate that no reaction between aldehyde and methoxyhydroperoxide occurs under our experimental conditions.

(27) P. Kolsaker and P. S. Bailey, *Acta Chem. Scand.*, 21, 537 (1967).

**Scheme V**



possible to determine the proportion following one path, the proportion of the other way being complementary, by measuring the amounts of olefin used (or of hydroperoxide formed) and the amounts of one carbonyl compound formed. Two examples are given in Tables IV and V, where the amounts of olefin used and of aromatic aldehyde formed are given. The ratio ArCHO formed/olefin used therefore indicates the proportion of cleavage which yields the particular aldehyde.

Table IV. Ozonization of Anethole; Proportion of Cleavage Yielding Anisaldehyde at 25°

| Ozone used, mmol | Olefin reacted, mmol | Anisaldehyde produced, mmol | Proportion of cleavage yielding anisaldehyde |
|---|---|---|---|
| 0.43 | 0.431 | 0.294 | 0.682 |
| 0.45 | 0.451 | 0.301 | 0.668 |
| 0.45 | 0.451 | 0.313 | 0.694 |
| 0.47 | 0.470 | 0.327 | 0.699 |
| 0.50 | 0.490 | 0.326 | 0.665 |
| 0.64 | 0.641 | 0.430 | 0.671 |

Table V. Ozonization of Cinnamyl Alcohol; Proportion of Cleavage Yielding Benzaldehyde at 25°

| Ozone used, mmol | Olefin reacted, mmol | Benzaldehyde formed, mmol | Proportion of cleavage yielding benzaldehyde |
|---|---|---|---|
| 0.27 | 0.271 | 0.0692 | 0.255 |
| 0.50 | 0.500 | 0.133 | 0.265 |
| 0.50 | 0.503 | 0.131 | 0.261 |
| 0.55 | 0.549 | 0.146 | 0.267 |
| 0.55 | 0.551 | 0.148 | 0.269 |
| 0.56 | 0.562 | 0.153 | 0.273 |
| 0.67 | 0.670 | 0.172 | 0.256 |

In some cases the proportions of cleavage have been studied at different temperatures (Table VI). Although the temperature interval explored is very limited, no significant change of the proportions of cleavage seems to occur by varying the temperature.

Further evidence on the significance of the electronic factors that may contribute to the direction of the two possible ways of cleavage has been obtained from the proportions of cleavage for a series of $\beta$-substituted styrenes, which also contain a substituent in the aromatic ring. The results which are reproduced in Table VII are expressed with a confidence limit $\geqslant 95\%$.

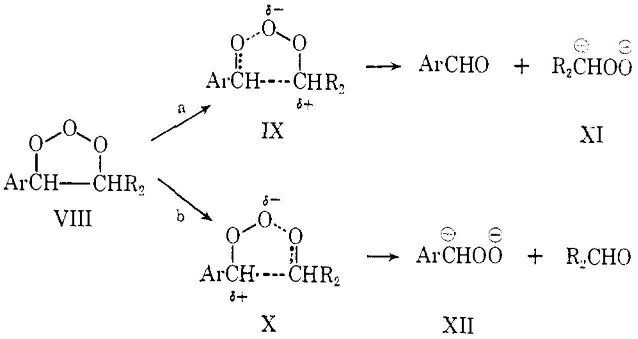
## Discussion

The instability of the primary ozonides even at low temperatures prevented, until recently, their detection. However, evidence for their existence has been obtained by Criegee and Schröder[24] (for the primary ozonide of *trans*-di-*t*-butylethylene), and by Greenwood[28] for the primary ozonides of some *trans*-alkenes. The 1,2,3-trioxolane structure (VIII) of the primary ozonide of *trans*-1,2-di-*t*-butylethylene was confirmed by Bailey[29] from low-temperature nmr experiments which indicate that both methine protons are equivalent. This five-membered ring structure is thus in agreement with the structure previously favored by Criegee.[16]

Although, in an earlier period, no primary ozonides have been observed for *cis*-olefins,[24,29] possibly because they are even more unstable than the *trans* isomers (at temperatures as low as $-110°$), Greenwood[30] reported some evidence for the existence of the *cis*-primary ozonides (at $-130°$ in dichlorodifluoromethane solutions) of but-2-ene, pent-2-ene, and hex-3-ene. While the evidence for a 1,2,3-trioxolane structure is not unambiguous for the *cis*-primary ozonides, an analogous structure to the *trans*-primary ozonides is suggested.

On the assumption that the 1,2,3-trioxolane structure (VIII) for the primary ozonides is correct, two ways of cleavage (a and b) will lead to two transition states, represented by IX and X, which will finally give the products indicated in Scheme VI.

**Scheme VI**



If $x$ is the proportion of the cleavage following path a, with a rate constant $k_a$, and hence, $1 - x$ the proportion of cleavage following path b, with a rate constant $k_b$, it follows that

$$x/(1 - x) = k_a/k_b \qquad (3)$$

if both reactions are of the same order.

From the theory of Wynne-Jones and Eyring[31] it can be deduced that

$$\log (k_a/k_b) = -(\Delta G_a^{\ddagger} - \Delta G_b^{\ddagger})/2.3\, RT = -\Delta\Delta G^{\ddagger}/2.3RT \qquad (4)$$

where $\Delta G_a^{\ddagger}$ and $\Delta G_b^{\ddagger}$ represent the activation energies accompanying the formation of the transition states IX and X, or states of similar structure.

It was shown in a previous study[20] that, since two different reaction paths a and b are considered, two reaction constants, $\rho_a$ and $\rho_b$, must be associated with these distinct reactions. However, only one Hammett substituent constant $\sigma$ needs to be considered in each

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(28) F. L. Greenwood, *J. Org. Chem.*, 29, 1321 (1964).

(29) P. S. Bailey, J. A. Thompson, and B. A. Shoulders, *J. Am. Chem. Soc.*, **88**, 4098 (1966).

(30) L. J. Durham and F. L. Greenwood, *Chem. Commun.*, 24 (1968); F. L. Greenwood, *J. Org. Chem.*, 30, 3108 (1965).

(31) W. F. K. Wynne-Jones and H. Eyring, *J. Chem. Phys.*, 3, 492 (1935).

Table VI. Proportions of Cleavage Yielding ArCHO at Different Temperatures

| Olefin | Temp, °C<br>0 | 15 ± 0.1 | 25 ± 0.1 | 35 ± 0.1 |
|---|---|---|---|---|
| Cinnamyl alcohol | 0.264 ± 0.020 | | 0.264 ± 0.006 | 0.263 ± 0.006 |
| Styrene | | 0.404 ± 0.037 | 0.407 ± 0.009 | 0.414 ± 0.006 |
| *p*-Chlorostyrene | | 0.567 ± 0.007 | 0.581 ± 0.045 | 0.563 ± 0.007 |
| Anethole | 0.682 ± 0.012 | | 0.680 ± 0.013 | 0.680 ± 0.008 |

Table VII. Proportions of Cleavage of $R_1C_6H_4CH{=}CHR$ Yielding the Aromatic Aldehyde at 25°

| | $R_2$ | | | | | | |
|---|---|---|---|---|---|---|---|
| $R_1$ | $COOCH_3$ | $CH_2OH$ | H | $C_6H_5$ | COOH | $CH_3$ | $COCH_3$ |
| *p*-$NO_2$ | | | 0.86 ± 0.03 | 0.91 ± 0.02 | | | |
| *m*-$NO_2$ | | | 0.84 ± 0.03 | | | | |
| *m*-Cl | 0.42 ± 0.02 | | 0.67 ± 0.02 | | 0.84 ± 0.05 | | |
| *p*-Cl | 0.36 ± 0.02 | 0.40 ± 0.02 | 0.57 ± 0.01 | 0.64 ± 0.01 | | 0.90 ± 0.01 | |
| H | 0.23 ± 0.01 | 0.26 ± 0.01 | 0.41 ± 0.01 | 0.500 | 0.61 ± 0.01 | 0.82 ± 0.01 | 0.90 ± 0.02 |
| *p*-$CH_3$ | | | 0.29 ± 0.01 | 0.39 ± 0.02 | 0.46 ± 0.02 | | |
| $CH_2O_2$ | | | | | | 0.75 ± 0.02 | 0.85 ± 0.01 |
| *p*-$OCH_3$ | | | 0.21 ± 0.04 | | 0.39 ± 0.02 | 0.68 ± 0.02 | 0.80 ± 0.02 |

case, since this constant is defined for the substituent in the aromatic ring, irrespective of the reaction path followed. Consequently, Hammett's relation may be written as shown in eq 5 and 6.[32]

$$\Delta G_a^{\ddagger} = \Delta G_{0,a}^{\ddagger} - 2.3RT\rho_a\sigma \tag{5}$$

$$\Delta G_b^{\ddagger} = \Delta G_{0,b}^{\ddagger} - 2.3RT\rho_b\sigma \tag{6}$$

From eq 3–6 the final equation (7) is obtained

$$\log [x/(1 - x)] = -\Delta\Delta G_0^{\ddagger}/2.3RT + (\rho_a - \rho_b)\sigma \tag{7}$$

where $\Delta\Delta G_0^{\ddagger} = \Delta G_{0,a}^{\ddagger} - \Delta G_{0,b}^{\ddagger}$ is the Gibbs energy difference between the transition states IX and X for compounds which have no substituent in the aromatic ring. The values of $\Delta\Delta G_0^{\ddagger} = -2.3RT \log [x/(1 - x)]$ (Table VIII) depend on the substituent in the $\beta$ position, *i.e.*, $R_2$; these $\Delta\Delta G_0^{\ddagger}$ values may be used for comparison of the electronic effects which can be attributed to the $\beta$ substituent in a series of $\beta$-substituted styrenes.

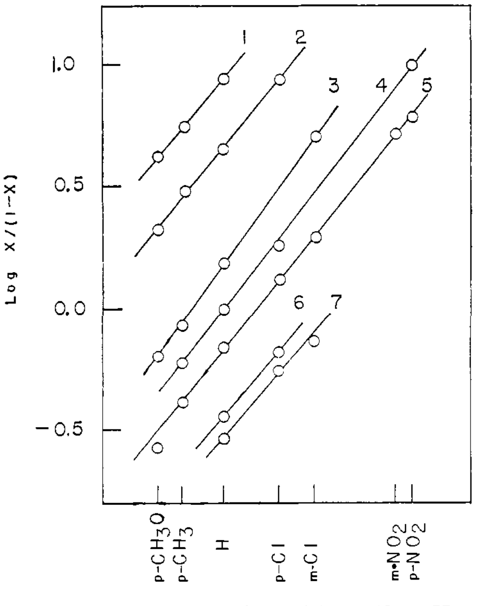

Figure 1. Verification of eq 7; log [$x$/(1 − $x$)] *vs.* Hammett's $\sigma$ constant: $R_2$ = $COCH_3$ (1), $CH_3$ (2), COOH (3), $C_6H_5$ (4), H (5), $CH_2OH$ (6), $COOCH_3$ (7).

Figure 1 represents the satisfactory agreement of eq 7 with the experimental results given in Table VII. This figure also reveals that, with the exception of the cinnamic acids, all the slopes (*i.e.*, $\rho_a - \rho_b$) are approximately the same. Table VIII presents the $\Delta\Delta G_0^{\ddagger}$ values for the different $\beta$-substituted styrenes, and the values of $\rho_a - \rho_b$ calculated by means of a least-square method for these $\beta$-substituted styrenes which have a substituent in the aromatic ring. From a comparison of these values of $\rho_a - \rho_b$, it appears that $\rho_a - \rho_b$ = 1.24 ± 0.04 adequately represents the slope that can be used in all the cases in eq 7. The discrepancy observed with the cinnamic acids may be explained by participation of hydrogen bondings which are known to occur between the acid molecules and between the acid and methanol molecules.

Table VIII

| $R_2$ | $\rho_a - \rho_b$ | $\Delta\Delta G_0^{\ddagger}$,[a] kcal/mol |
|---|---|---|
| $COCH_3$ | 1.21 | −1.28 |
| $CH_3$ | 1.24 | −0.90 |
| COOH | 1.38 | −0.24 |
| $C_6H_5$ | 1.28 | 0.00 |
| H | 1.25 | 0.23 |
| $CH_2OH$ | 1.24 | 0.61 |
| $COOCH_3$ | 1.20 | 0.74 |

[a] At 25°.

The similarity of the slopes in Figure 1 shows that $\rho_a - \rho_b$ is (with the exception mentioned) independent of the $\beta$ substituent $R_2$, which implies that $R_2$ always causes the same effect, evaluated in terms of $\Delta\Delta G_0^{\ddagger}$ values, whatever the nature of $R_1$. This observation leads to the possible suggestion that the $\beta$ substituent influences the proportions of the two ways of cleavage always in the same manner, irrespective of the $\alpha$ substituent. This conclusion, however, is based only on results for compounds with substituted phenyl groups in the $\alpha$ position and does not necessarily imply that

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(32) K. J. Laidler, "Chemical Kinetics," McGraw-Hill Book Co., Inc., New York, N. Y., 1965, p 248.

this is also the case when substituents, other than substituted phenyl groups, are found in the $\alpha$ position. Further studies are in progress to clarify this point.

The agreement of the experimental values of Table VII with eq 7, which expresses quantitatively the qualitative predictions that can be drawn from the classical inductive and mesomeric effects, facilitates the interpretation of the presented results. This interpretation is summarized below, reference being made to the two transition states IX and X, or states approaching structures IX and X.

In the case of the stilbene, $\Delta\Delta G^{\ddagger} = \Delta\Delta G_0^{\ddagger} = 0$, for symmetry reasons. Electron-releasing substituents (for example $p$-$CH_3$) increase the electron density at the carbon atom attached to the zwitterionic carbocation and will contribute to the zwitterion stabilization. This will result in the lowering of the energy of transition state X, compared to that of IX,[33] and hence path b will be favored. Conversely, electron-withdrawing substituents will decrease the stabilizing effect of the phenyl group and, consequently, $\Delta G_a^{\ddagger} < \Delta G_b^{\ddagger}$, which will result in an enhancement of the proportion of cleavage following path a.

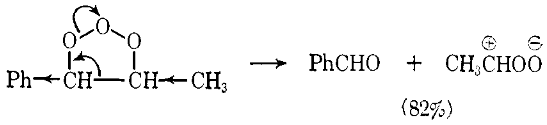
It is thus concluded that the zwitterion which is preferentially formed is the one whose environment is better able to stabilize the positive charge by increasing the electron density in the vicinity of the carbocation *via* inductive and mesomeric effects.

Similar conclusions can be drawn for any one of the other series having a common $\beta$ substituent and where only the ring substituent is varied. In the case of styrene, for example, the energy of X is less than that of IX because the phenyl group stabilizes the positive charge of the zwitterion ($\Delta\Delta G_0^{\ddagger} = 0.23$ kcal/mol). The state X is therefore favored with respect to IX, and less than 50% of the cleavage will follow path a. Again, electron-releasing substituents on the aromatic ring will increase the electron density at the carbon atom attached to the zwitterionic carbocation. This will contribute to stabilize the zwitterion and, consequently, to lower the energy of X with respect to IX, favoring thus path b.

Any discussion of the electronic effects due to groups $R_2$ attached to an ethylenic carbon atom is less straightforward than the discussion of the Hammett relationships (eq 7). A consideration of the relative efficiencies of the different groups in stabilizing zwitterions in the order indicated by Table VIII, *i.e.*, $COCH_3 > CH_3 > COOH > Ph > H > CH_2OH > COOCH_3$, shows that this order is unusual, in terms of classical organic chemistry, in that the electron-donating and -attracting groups alternate in this sequence.

Inspection of the results (Table VII) when these are expressed in terms of a Hammett relationship demonstrate that *electron-donating groups attached to a potential zwitterionic carbocation (in the transition state) favor the formation of that particular zwitterion, while electron-withdrawing groups act in the opposite way.* The same argument will be used for discussing the effects of the $R_2$ groups.

Bailey's results[21] from 1-methyl-1,2-dibenzoylethylene, in addition to Keaveney's findings,[22] confirm the present results, *i.e.*, that the electron-donating methyl group favors the zwitterion formation at the carbon atom to which the methyl group is attached. The influence of the methyl group in $\beta$-methylstyrene can thus be deduced from an observation that the effects of the substituents are codirectional and that the stabilizing influence of the methyl group is due to its inductive effect.



Bailey's observations on 1,2-dibenzoyl-1-methoxyethylene[21] showed that the electron-withdrawing methoxy group considerably reduces the zwitterion formation at the carbon atom to which the methoxy group was attached. It may thus be concluded that polarization, due to combined inductive effects of the substituents, controlled the direction of cleavage. However, the results obtained with vinyl methyl ether indicate that this olefin cleaves to give $CH_3OC^+HOO^- + HCHO$ in a proportion of approximately 45%, thus showing that the destabilizing effect of the methoxy group should not be overemphasized. In this case, the possible contribution of some resonance stabilization should not be excluded. The behavior of the $OC(O)CH_3$ group, which results in the formation of only 24% of $CH_3C(O)OC^+HOO^- + HCHO$ in the ozonolysis of vinyl acetate, clearly illustrates that electron-withdrawing groups reduce, as a rule, the zwitterion formation at the carbon atom to which these groups are attached. These observations are confirmed by the present results, obtained with the electron-withdrawing groups $R_2 = CH_2OH$ and $COOCH_3$, both of which lead to the formation of only relatively small amounts of $R_2C^+HOO^-$.

The phenyl ring appears to contribute to the zwitterion stabilization (or to the stabilization of the potential zwitterion when in its transition state) by some resonance effect. However, when the results obtained with styrene are considered, it appears that the relatively low value for the energy difference ($\Delta\Delta G_0^{\ddagger} = 0.23$ kcal/mol) between states IX and X, which is reflected by the observation that the most favored path is followed in a proportion of only 59%, is an indication of the relatively weak stability conferred by the benzene ring. This agrees with previous reports.[21,22] which indicate that the resonance contribution appears to have little influence in directing the ways of cleavage of the primary ozonides. The relatively poor stability conferred by the phenyl group is also apparent when the results obtained with *trans*-$\beta$-methylstyrene, where 82% of $CH_3C^+HOO^- + PhCHO$ is formed, are considered. The inductive effect of the methyl group largely "overplays" the effect of the phenyl group.

The behavior of the $COCH_3$ and COOH groups which tend to stabilize the zwitterions $R_2C^+HOO^-$ despite the fact that they are electron-withdrawing groups, may be interpreted as follows. It will be assumed that the transition states arising during the cleavage of the primary ozonides can not only possess structures IX and X (Scheme VI) but can also approach the structures XIII and XIV (Scheme VII).[34]

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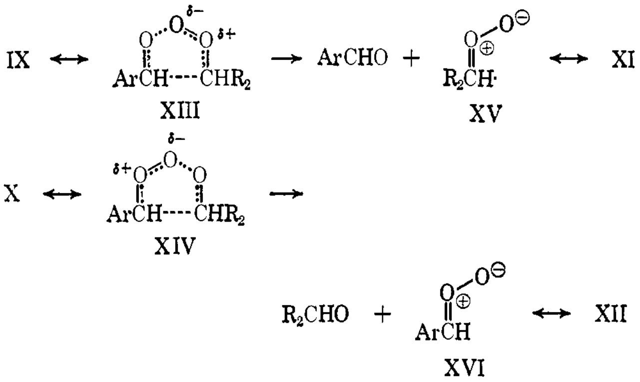
(33) It follows from eq 3 and 4 that $\Delta\Delta G^{\ddagger} = \Delta G_a^{\ddagger} - \Delta G_b^{\ddagger} = -2.3\ RT \log [x/(1-x)]$. For 4-methylstilbene, $x = 0.39$ (Table VII) and, consequently, $\Delta\Delta G^{\ddagger} = 0.26$ kcal/mol (at 25°). The form X is thus favored by 0.26 kcal/mol with respect to IX.

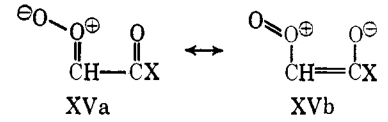
(34) The zwitterion structures XV and XVI, and their implication in directing the ozonide *cis/trans* distributions, have been discussed recently.[1,16,17]

**Scheme VII**



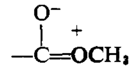
For the zwitterion XV ↔ XI, the following resonance may occur when $R_2 = C(=O)X$ (Scheme VIII).

**Scheme VIII**



When $R_2 = COCH_3$, *i.e.*, $X = CH_3$, the contribution of XVb will be important because the methyl group favors electron delocalization. Thus any participation of the mesomeric form XVb would favor the formation of this zwitterion, hence path a.

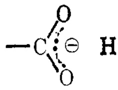
If, however, $R_2 = COOCH_3$, *i.e.*, $X = OCH_3$, the participation of the mesomeric form



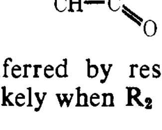
$$-\overset{O^-}{\overset{|}{C}}=\overset{+}{O}CH_3$$

of the ester function reduces the possibility of any stability being conferred by resonance as depicted by Scheme VIII and hence the possibility of stabilizing the zwitterion XV ↔ XI is decreased. This can explain the observation that the ester group exerts its influence on the direction of cleavage mainly by its inductive effect.

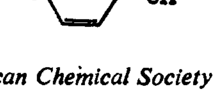
Finally, when $R_2 = COOH$, *i.e.*, OH, the participation of the mesomeric form



to the structure of the carboxyl group may not be as effective in hindering the resonance stabilization shown in Scheme VIII as is the ester group, owing to the small inductive effect of the H atom. Moreover, a consideration of the possible participation of hydrogen bonding in the zwitterion may explain the efficiency of the carboxyl group in its ability to stabilize this zwitterion.



The stability conferred by resonance described in Scheme VIII is unlikely when $R_2$ = Ph. The mesomeric form



would be involved and favored by electron-withdrawing *para* substituents. This is in variance with the present results, which show that the presence of a $p$-$NO_2$ substituent reduces the formation of aromatic zwitterion. The weak stabilization contributed by the phenyl ring can be interpreted in terms of structures XVI ↔ XII. A more important contribution of a transition state approaching form X may play a role, particularly when an electron-donating substituent is located in the *para* position of the phenyl ring.

In conclusion, the results presented here indicate that the transition state for path a can be represented more adequately by a combination of structures IX with XIII, and similarly the transition state corresponding to path b by a combination of X and XIV. In the case of the aromatic substituents, the participation of form XIV may explain the weak resonance stabilization contributed by the phenyl ring, but the effects described in terms of Hammett relationships seem to indicate an important contribution of a form which approaches structure X.

Finally, the results reported in Table VI indicate that, in those cases which have been examined, the proportions of the two ways of cleavage do not vary within the temperature range studied. However, owing to the low values of the corresponding $\Delta\Delta G^{\ddagger}$ quantities, this observation does not prove unambiguously that $\Delta H_a \approx \Delta H_b$ nor, therefore, that the entropy factors (which may be related to the vibrational states of the transition states, are the only ones which govern the direction of cleavage of the primary ozonides.

## Experimental Section

**Ozonolysis Procedure.** The technique of ozonolysis, using $O_2$–$O_3$ mixtures, together with the dosimetry of ozone, has been described previously.[8a] The ozone output was varied between 0.07 and 0.2 mmol of $O_3$/min. The ozone used was limited to less than 80% of the theoretical amount, in order to prevent autoxidation of aldehydes to peracids; this is enhanced by ozone in the absence of olefin, which prevents this autoxidation.

The solvent used was 1.0 $M$ $CH_3OH$ in $CCl_4$. In most of the experiments the initial concentration of olefin was 0.05 $M$. When lower concentrations were necessary due to solubility reasons, the initial olefin concentrations were: 0.03 $M$ for the *p*-methyl- and *m*-chlorocinnamic acids, 0.02 $M$ for the *p*-methoxy and *p*-nitrocinnamic acids, and 0.015 $M$ for the 4-nitrostilbene. The concentration of 0.1 $M$ was used for the ring-substituted styrenes and for the compounds having no substituent in the phenyl ring and $R_2$ = $COCH_3$, $CH_3$, COOH, $CH_2OH$, and $COOCH_3$.

The time required for the ozonolysis never exceeded 15 min. It can therefore be assumed that the amounts of aldehydes and hydroperoxides, which were measured immediately after completion of the ozonolysis, had not been affected by secondary reactions, such as a slow decomposition of the hydroperoxides or an autoxidation of the aldehydes. This is confirmed by the observations reported below concerning the relative stability of the hydroperoxides under our experimental conditions and by the observation that no infrared bands corresponding to peracids were observed.

**The amounts of hydroperoxides** were measured by an analytical procedure similar to that described by Lohaus;[35] 2–5 ml of the solution to be analyzed was added to 25 ml of pure acetic acid containing 1 g of NaI, in the presence of solid $CO_2$. After 5 min in the dark, this mixture was poured into 100 ml of water and the iodine titrated with 0.1 $N$ sodium thiosulfate. A blank titration was carried out. The analyses made under these conditions were very reproducible, providing they were carried out shortly after completion of the ozonolysis; the values found for the hydroperoxides decreased by only a few per cent 1 hr after ozonolysis.

**The aromatic aldehydes** were analyzed to determine the proportion of cleavage of the β-methylstyrenes by infrared spectroscopy in a

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(35) G. Lohaus, *Ann. Chem.*, **583**, 4 (1953).

manner similar to that used previously for ring-substituted styrenes.[20] The amounts of benzophenone formed during the methanolic ozonolyses of triphenylethylene were also measured by infrared spectroscopy. The acetaldehyde formed during the ozonolysis of the $\beta$-methylstyrenes did not interfere with the spectroscopic measurements of the intensities of the carbonyl bands in the region of 1700–1712 cm$^{-1}$, since this aldehyde is very rapidly transformed to its hemiacetal by the methanol present in the solvent. The formation of hemiacetal of the aromatic aldehydes was checked using standard solutions of the aldehydes in the presence of 1.0 $M$ $CH_3OH$. No appreciable effect on the intensity of the carbonyl band was observed and hence the formation of hemiacetal was negligible under these experimental conditions. The aromatic aldehydes used for the infrared calibration curves were dissolved in $CCl_4$, in the presence of 1.0 $M$ $CH_3OH$. The results obtained in this way were compared with the proportions of aldehyde formed as determined by gas chromatography.

**The gas chromatographic analyses** were performed using a 5750 F & M gas chromatograph, using a flame detector. Six-foot columns of 10% Hyprose on Chromosorb P, or of Silicone Rubber UC W 98 were used. After the ozonization, the solvent loss due to evaporation during the ozonolysis was carefully compensated and 5-$\mu$l samples were injected in the gas chromatograph. The chromatograms were integrated by means of a planimeter and the area under the peak corresponding to the olefin which did not react and also to the aldehydes which were formed were compared to the areas under the peaks obtained under the same conditions using standard samples of the appropriate substances. The analyses were repeated a minimum of five times. The reproducibility is illustrated by the following example, which gives the areas measured for five different injections of a 0.05 $M$ benzaldehyde solution in $CCl_4$, in the presence of 1.0 $M$ $CH_3OH$: 15.19, 15.36, 15.74, 15.15, and 15.37 cm$^2$. For each substance five to ten experiments were carried out to determine the proportion of cleavage; two different oven temperatures were used with no effect on the results. The results reported in Table VII have been calculated with a confidence limit ≥95%.

**Acknowledgment.** The authors express their gratitude to Professor D. Gravel for helpful discussions and to Mr. J. Grignon for assistance in performing the experimental work. The financial support given by the National Research Council of Canada is gratefully acknowledged.

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# Unusual Metalloporphyrins. III. Induced Oxidation of Cobalt(II) and Iron(II) Porphyrins by Unsaturated Hydrocarbons[1]

**M. Tsutsui, R. A. Velapoldi, L. Hoffman, K. Suzuki, and A. Ferrari**

*Contribution from the Department of Chemistry, New York University,*
*Bronx, New York 10453. Received October 16, 1968*

**Abstract:** The induced oxidations of cobalt(II) and iron(II) porphyrins by unsaturated hydrocarbons are described. The oxidation reactions were characterized experimentally and by wavelength-absorption shifts in the visible spectra. Metal–olefin interactions were shown by *cis*- to *trans*-2-butene isomerizations. Unsaturated hydrocarbons are classified into two categories: class I, which cause immediate oxidation, include unsaturated hydrocarbons with isolated double or triple bonds; class II, which cause slower oxidation, include unsaturated hydrocarbons with conjugated double or triple bonds. The reversible solvent caused oxidation of the cobalt porphyrins is discussed.

Metalloporphyrins play an important role in many chemical processes which are essential to life. Cellular respiration, an important biological process, is dependent upon these pyrrole pigments. Only in the last 20 years, however, has the important fundamental role of hematin compounds in the process of cellular respiration become evident. In cellular respiration, the chemical energy of the organic substances is made available for a variety of different energy requirements of the living cell.

In addition to the respiratory enzyme (cytochrome oxidase) and a variety of cytochromes, other hematin enzymes such as catalase and peroxidase are found in the cells of aerobic organisms. It is proposed[2] that these enzymes interact with ligands by $\pi$ bonding. In these biological compounds, it is the metal in the metalloporphyrin moiety which would $\pi$ bond to the ligand. An investigation of the reactions of $\pi$-bonding ligands such as olefins[3] with metalloporphyrins was undertaken to elucidate the mechanism of $\pi$ interaction. In addition, information determined from this investigation might provide insight into the controversial bonding mode of oxygen in oxyhemoglobin and myoglobin which is thought to be of the $\pi$-bonding type.[4]

During this investigation, it was discovered that addition of unsaturated hydrocarbons to cobalt(II) porphyrins caused immediate oxidation of the Co(II) to Co(III) followed by degradation.[1b] This reaction was applied to the biologically important iron(II) porphyrin systems and these results in addition to those of the cobalt oxidation are presented in this paper.

## Experimental Section

**Reagents and Solvents.** All solvents used were reagent grade and were further purified by distillation under nitrogen from respective

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(1) (a) Supported by National Science Foundation Grant GB-5732. (b) Preliminary results of this work were reported: M. Tsutsui, R. A. Velapoldi, K. Suzuki, and A. Ferrari, *J. Am. Chem. Soc.*, **90**, 2723 (1968).

(2) Conference of Prospectives of $\pi$-Interactions in Biological Systems, New York Academy of Sciences, New York, N. Y., March 28, 1967.

(3) It has been proposed that olefins are plant hormones since they appear to regulate certain growth functions in plants: J. D. Goeschl, H. K. Pratt, and B. A. Bonner, *Plant Physiol.*, **42**, 1077 (1967); J. D. Goeschl, L. Rappaport, and H. K. Pratt, *ibid.*, **41**, 877 (1966); S. P. Burg and E. A. Burg, *Proc. Natl. Acad. Sci. U. S.*, **55**, 262 (1966).

(4) Original reference which proposed $\pi$ bonding: L. Pauling and C. D. Coryell, *ibid.*, **22**, 159 (1936).

*Tsutsui, et al. / Oxidation of Co(II) and Fe(II) Porphyrins*