Crossed Ozonide Formation in the Ozonolysis of Styrene

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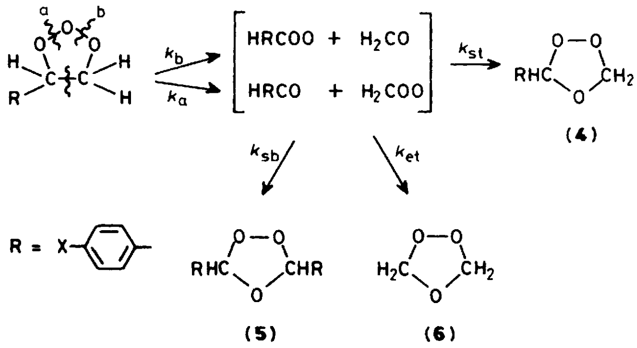
Styrene–benzaldehyde mixtures (unsubstituted and the *p*-nitro, *p*-chloro, and *p*-methyl systems) were ozonized in $CDCl_3$ at 0 °C. The yields of styrene ozonide and of the two crossed ozonides (stilbene and ethylene ozonides) were determined. The cleavage direction ratios of the primary ozonides were also determined. In a computer simulation of the yields five rate expressions were employed, giving relative rate coefficient information on the cycloaddition reactions between the carbonyl oxides and the aldehydes. This analysis of the various competing reactions during ozonolysis indicated that electron-withdrawing substituents increased crossed ozonide formation by enhancing the dipolar character of the carbonyl oxide and the dipolarophilicity of the aldehyde. The substituent also influences the cleavage direction of the primary ozonide and the solvent cage effect. A Hammett correlation of the crossed ozonide rate constants [k(stilbene ozonide)/(k(ethylene ozonide)] had a slope (ρ) of 1.4 (0.1).

Kinetic studies of the three-step Criegee mechanism of ozonolysis (Scheme 1) have been carried out for a variety of alkenes;[1] the study of styrene and its derivatives has been particularly fruitful. Fliszár *et al.* have shown that there is a correlation between the rates of reactions (i) and (ii) and the substitutent on styrene. In reaction (i), a negative ρ value (-0.9 to -1.0) indicated that ozone attack was electrophilic in nature.[2a,b] In reaction (ii), the cleavage direction of the primary ozonide (**1**) was assisted by electron-donating substituents which stabilize the positive charge on the incipient carbonyl oxide (**2**).[2c,d] However, kinetic studies of the effect of substituents on reaction (iii) have not been reported, undoubtedly because the high reactivity of the carbonyl oxide makes experimental studies difficult.[3]

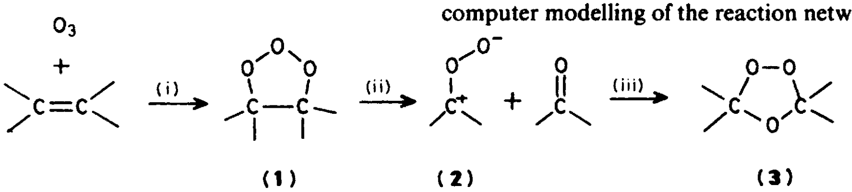
We recently observed[4] that the ozonolyses of styrene and *p*-nitrostyrene gave strikingly different amounts of the normal and crossed ozonides (Scheme 2). From styrene, the three ozonides (**4**)—(**6**) (of styrene, stilbene, and ethylene) were formed in relative amounts 93:1:6 while from *p*-nitrostyrene the ratios were 63:22:15. Crossed ozonide formation from unsymmetrical alkenes is qualitatively explained in Scheme 2; however there has been little effort to understand the diversity in the ozonide yields from various substrates, apart from some recent studies of propylene and [1,1-$^2H_2$]ethylene.[5]

A more analytical rationalization of the normal and crossed ozonide yields for the styrene systems requires some evaluation of the competitive reactions occurring during ozonolysis. These yields are influenced by the cleavage direction of the primary ozonide in step (ii), the reactivities of the carbonyl oxide and carbonyl compounds in step (iii), and solvent cage effects. A simple kinetic model can incorporate solvent cage effects in the reaction rate coefficients and reduce the ozonide formation to the five competitive reactions shown in Scheme 2. Although relative values for the two alternative cleavage direction coefficients k_a and k_b can be obtained by standard trapping experiments in alcohol[2c,d] no estimates are available for k_{et}, k_{st}, k_{sb}. Consequently it becomes difficult dependably to anticipate the trends in ozonide yields either qualitatively or quantitatively.



Scheme 2.

The unequal crossed ozonide yields reflect the importance of various competing processes. More specifically, they contain information on the magnitudes of k_{st}, k_{sb}, and k_{et}. Success has been achieved in using such yield results to make some quantitative inferences about such kinetic parameters.[5] The analysis employs a computer model of the reaction kinetics which fits the observed results. Only relative rate coefficients can be obtained by such an approach, but such relationships can still provide useful insights into the comparative reactivity of the various carbonyl oxides and aldehyde dipolarophiles in this classic 1,3-dipolar cycloaddition. Of course, such an approach would not be feasible if the three ozonide-producing cycloadditions were the only paths for carbonyl oxide consumption. Mass balance would then dictate that the two crossed ozonides would be formed in equal amounts, even if $k_{sb} \neq k_{et}$. However, ozonide yields are rarely quantitative, since side reactions of carbonyl oxides form dimers, oligimers, and other products. Such reactions in essence quench ozonide formation. Therefore we decided to explore combining the ozonide yields with computer modelling of the reaction network in Scheme 2 in the



Scheme 1.

Table. Ozonolysis of p-$RC_6H_4CH{=}CH_2$ in the presence of p-RC_6H_4CHO; observed[a] and calculated[b] yields

R	Run	[p-RC_6H_4CHO] mol dm^{-3}	% Styrene ozonide		%Stilbene ozonide[c]		% Ethylene ozonide		k_{st}[d]	k_{sb}	k_{et}	k_a	k_b
			Obs.	Calc.	Obs.	Calc.	Obs.	Calc.					
p-NO_2	1	0.00	62.8 (1.4)[e]	62.9	22.3 (1.2)	21.9	14.8 (1.0)	15.1	0.11	0.15	0.10	0.78	0.22
	2	0.06	60.3 (1.8)	59.6	30.0 (1.4)	30.4	9.7 (0.6)	10.0	0.11	0.23	0.10	0.78	0.22
	3	0.10	60.4 (0.9)	60.8	31.0 (1.1)	30.7	8.6 (0.5)	8.5	0.11	0.23	0.10	0.78	0.22
	4	0.12	61.2 (1.0)	61.3	31.0 (0.8)	30.8	7.9 (0.6)	7.9	0.11	0.23	0.10	0.78	0.22
	5	0.20	64.7 (1.3)	63.1	30.1 (0.9)	30.8	5.3 (0.6)	6.2	0.11	0.23	0.10	0.78	0.22
p-Cl	6	0.00	90.2 (1.4)	89.8	2.2 (0.1)	2.5	7.6 (1.3)	7.7	0.55	0.03	0.10	0.56	0.44
	7	0.06	87.9 (1.4)	87.1	5.4 (0.4)	5.2	6.7 (1.1)	7.8	0.35	0.03	0.10	0.56	0.44
	8	0.10	86.7 (1.3)	86.3	6.9 (0.5)	6.5	6.4 (0.9)	7.2	0.31	0.03	0.10	0.56	0.44
	9	0.12	86.2 (0.7)	86.1	7.5 (0.2)	7.1	6.3 (0.7)	6.8	0.31	0.03	0.10	0.56	0.44
	10	0.20	84.4 (1.0)	85.7	10.1 (0.8)	9.1	5.5 (0.5)	5.2	0.29	0.03	0.10	0.56	0.44
H	11	0.00	93.3 (0.7)	92.8	1.5 (0.4)	1.2	5.2 (0.6)	5.8	0.57	0.021	0.10	0.27	0.73
	12	0.06	92.6 (0.5)	92.6	2.9 (0.4)	3.1	4.5 (0.5)	4.3	0.52	0.021	0.10	0.27	0.73
	13	0.10	91.9 (0.7)	92.0	3.9 (0.4)	4.3	4.3 (0.3)	3.7	0.50	0.021	0.10	0.27	0.73
	14	0.12	91.4 (0.8)	91.8	4.7 (0.6)	4.8	3.8 (0.4)	3.4	0.50	0.021	0.10	0.27	0.73
	15	0.20	90.8 (0.4)	90.7	6.1 (0.3)	6.7	3.1 (0.2)	2.6	0.50	0.021	0.10	0.27	0.73
p-Me	16	0.00	95.1 (0.6)	94.7	0.6 (0.1)	0.5	4.4 (0.7)	4.8	0.63	0.01	0.10	0.25	0.75
	17	0.06	95.7 (0.7)	95.1	1.1 (0.2)	1.1	3.2 (0.6)	3.8	0.63	0.01	0.10	0.25	0.75
	18	0.10	94.8 (0.3)	95.1	2.2 (0.6)	1.5	2.9 (0.5)	3.4	0.60	0.01	0.10	0.25	0.75
	19	0.12	95.3 (0.6)	95.0	1.9 (0.2)	1.7	2.8 (0.4)	3.3	0.59	0.01	0.10	0.25	0.75
	20	0.20	94.9 (0.5)	95.0	2.9 (0.3)	2.4	2.2 (0.3)	2.6	0.59	0.01	0.10	0.25	0.75

[a] Reactions in $CDCl_3$ at 0 °C; [alkene] = 0.2M, O_3:alkene = 0.8:1; relative ozonide yields from proton n.m.r. [b] Calculated using the network in Scheme 2, bimolecular rate constants k_{st}, k_{sb}, k_{et}, and unimolecular rate constants k_a and k_b. The yields were obtained by numerical summation of the rate equations for small reaction increments until the absolute ozonide yield was reached. Only the relative values of the rate constants are significant. [c] *cis*- and *trans*-stilbene ozonide. [d] Rate coefficients are defined according to Scheme 2; see also footnote *b*. [e] Standard deviaton (1σ) from 5—7 runs.

hopes of obtaining more insight into the third step of the Criegee mechanism. In order to provide an analysis for a range of 1,3-dipoles and dipolarophiles, styrene and its *p*-nitro, *p*-chloro, and *p*-methyl derivatives were chosen for study.

Results and Discussion

Styrene (or its substituted analogue) was ozonized in the presence of various concentrations of an added benzaldehyde identical with that produced from the primary ozonide breakdown. Addition of the aldehyde was expected to alter systematically the ozonide yields and provide additional data points for the kinetic fitting. Deuteriochloroform was chosen as the solvent since its polarity was expected to enhance solubilities, promote crossed ozonide formation, and enable ozonide yields to be determined from the proton n.m.r. spectra of the reaction mixture after ozonolysis. The average yields obtained are given in the Table.

It can be seen that the relative amounts of the crossed ozonides are largest for *p*-nitrostyrene and decrease with substitution of less electron-withdrawing groups. Also the ratio of the two crossed ozonides (stilbene ozonide and ethylene ozonide) varies from about 1.6:1 to 1:10 through the styrene series.

In order to interpret these yields, information on the cleavage direction of the primary ozonide is needed. The results obtained in $CDCl_3$–CH_3OH solutions are given in the Table under the columns k_a and k_b. The methoxy hydroperoxides used to obtain the ratio k_a:k_b were estimated from an n.m.r. assay of the reaction mixture. The cleavage ratios are similar to those obtained in CCl_4[2c,d] except that k_a:k_b was usually a little greater in that solvent.

The kinetic model of Scheme 2 was used to match the relative ozonide yields. Initial values were employed for the primary ozonide and added benzaldehyde concentrations consistent with the experimental stoicheiometry. The cleavage of the primary ozonide was described as two competing unimolecular reactions (k_a,k_b). The bimolecular reaction to give ethylene ozonide was kept fixed with k_{et} = 0.1 for all calculations while k_{st} and k_{sb} were varied to match the experimental results. The calculation was terminated when the total ozonide yield matched the observed yields. The best fits to the experimental results are listed in the Table under calculated yields.

For this simple model to be useful, one set of relative rate constants k_{st}, k_{sb}, and k_{et} should fit the yield results as the added benzaldehyde concentration is varied for a given styrene. This criterion is met for most of the results, with a few exceptions. The small systematic changes observed in k_{st} for runs 7—10, 11—15, and 16—20 may have several sources, such as solvent restructuring, sensitivity of the cleavage direction (k_a:k_b) to the added benzaldehydes, or changing solvent cage effects, but are not seriously troublesome. The reason for the more striking changes needed to get agreement for runs 1 (k_{sb}) and 6 (k_{st}) seems obscure. Apart from these qualifications, the general trends in the experimental yields can be reasonably approximated. The changes in k_{st} and especially k_{sb} for the four systems are defined clearly enough to be worthy of discussion.

The values of k_{sb} and k_{et} provide some insight into the reasons for yield variations. They reflect the relative recombination rates of the respective carbonyl oxides and aldehydes after their escape from the original solvent cage in which they had been formed. In the *p*-nitro system, the cycloadditon of the substituted carbonyl oxide and the benzaldehyde is favoured over the combination of H_2COO and H_2CO by a factor of 1.5—2.5. However, the substituted species are less reactive than H_2COO and H_2CO in the other three systems. Alternatively, if k_{sb} is compared between systems, the *p*-nitro-substituted carbonyl oxide and benzaldehyde are 8—20-fold more reactive than the other three pairs of PhHCOO and PhCHO. Furthermore, the regular change in k_{sb} or more precisely in k_{sb}:k_{et} follows a Hammett correlation (σ; see ref. 6) with a slope of 1.4 (0.1) (Figure). This positive slope implies that increasing the electron-withdrawing strength of the substituents assists the cycloaddition reaction, presumably by accentuating the positive

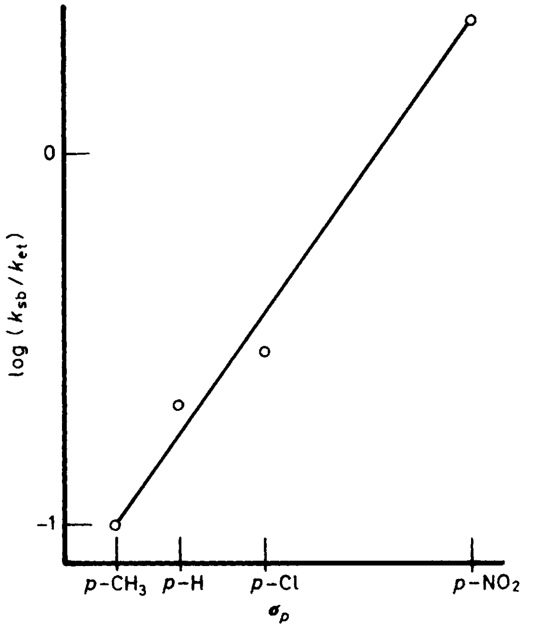


Figure. Hammett correlation of the stilbene and ethylene crossed ozonide rate constants [ρ = 1.4 (0.1)]

charge at the carbon centre in the carbonyl oxide and the benzaldehyde. In summary, the systematic increase in the stilbene ozonide : ethylene ozonide ratio in progressing from the *p*-methyl to the *p*-nitro system can be attributed to this electronic effect. Whether the enhanced 1,3-dipolar character of the substituted carbonyl oxide or the higher dipolarophilicity of the aldehyde may be the more important factor in the rate acceleration cannot be determined.

The interpretation for the change in k_{st} between the *p*-nitro and *p*-methyl systems (six-fold variation) is less straightforward. Styrene ozonide can be formed by four reactions involving recombination of PhCHOO + H_2CO or PhCHO + H_2COO in their original solvent cage (in-cage) or after escape from this solvent shell (out-of-cage). The kinetic analysis employing a single k_{st} does not distinguish among these processes. This makes a Hammett correlation inappropriate. It makes the most sense to attribute the relative increase in k_{st} and in the styrene ozonide yields when progressing from the polar *p*-nitro system to the relatively non-polar styrene and *p*-methylstyrene systems to an increase in the solvent cage effect and in-cage recombination. Such increases in the amounts of normal ozonide often accompany a decrease in the solvent polarity;[7] likewise a decrease in the polarity of the carbonyl oxide and dipolarophile should lead to less escape from the original solvent cage and more normal ozonide formation. The polarity changes in the carbonyl oxides and benzaldehydes should vary markedly, in view of the dipole moments of nitrobenzene (4.5 D), chlorobenzene (1.7 D), styrene (*ca.* 0.0 D), and toluene (0.4 D).[8]

The analysis of the yield results has provided a reasonable framework for understanding the competing reactions occurring during ozonolysis of these asymmetric alkenes. The Criegee mechanism is reasonably tractable to such a reaction network analysis. This helps to identifiy the structure–reactivity trends of substituted carbonyl oxides (1,3-dipoles) and dipolarophiles, and overall provides a more concrete description of the final stages of the Criegee reaction mechanism. The changes in ozonide yields seem neither adventitious nor inscrutable.

The limitations of this approach should be noted. It is difficult to estimate the accuracy of the relative rate coefficient ratios (k_{sb}:k_{et}). The kinetic model considerably simplifies a complex reaction process. The neglect of the non-ozonide-producing reactions (formation of polymeric peroxides, carbonyl oxide dimers, *etc.*) introduces one ambiguity since these reactions also affect the concentrations of the reactants. Presumably their neglect does not seriously affect the ozonide relative rate coefficients since the non-ozonide-forming reactions occur at rates which obviously do not dramatically alter the relative concentrations of the reactants. Added aldehydes are also well known sometimes to affect ozonide yields by perhaps altering the basic mechanism.[9] Such complications are probably not a serious problem here in view of the relatively low concentration of the added aldehyde, and their modest effects on the overall yields as well as other studies[10] which show that the cleavage direction of the primary ozonide is not seriously altered in different solvents. Nevertheless, it is not possible completely to evaluate the precise magnitude of such effects, which implies that some caution should be exercised in the quantitative use of the relative rate coefficients especially when comparisons are made with non-ozonolysis situations. Conversely, it would be useful to have some independent cross-checks of the crossed ozonide rate coefficient ratios as a guide to establishing whether this approach can be considered more than heuristic and semi-quantitative. Such information for these 1,3-dipoles and dipolarophiles is apparently not available. Perhaps this work will stimulate some efforts towards that end.

Experimental

^{1}H N.m.r. data were obtained with a Bruker WM-360 spectrometer. A Welsbach T-408 ozone generator was employed.

Materials.—The styrene and benzaldehyde substrates were obtained from Aldrich Co., with the exception of *p*-nitrostyrene (Polysciences) and *p*-methoxybenzaldehyde (Sigma). The styrenes were used without further purification. The benzaldehydes were purified by distillation and/or by taking advantage of differential solubilities. The $CDCl_3$ was distilled before use. Methanol was dried over 3 Å molecular sieves activated by heating at 150 °C for several hours while pumping on a vacuum line.

Ozonolysis Procedure.—A given styrene (1 mmol) (Table) and one of five amounts (0, 0.3, 0.5, 0.6, and 1.0 mmol) of the corresponding benzaldehyde were dissolved in $CDCl_3$ (5 ml) at 0 °C. 80% of the stoicheiometric amount of O_3 was passed as an O_3–O_2 mixture (calibrated iodometrically to 0.08 to 0.2 mmol of O_3 per minute). After the reaction a sample was withdrawn directly from the vessel and placed in a Wilmad 528 n.m.r. tube. It was stored at -20 °C until the spectrum was taken. The relative yields of stilbene, styrene, and ethylene ozonides were determined along with unchanged styrene from integration of the separated proton peaks in the region δ 5.0—6.8.[5,10] The average of results from 5—7 ozonolyses for each benzaldehyde concentration is given in the Table. Overall ozonide yields were estimated by comparing the amounts of ozonides and unchanged styrene. This is a sufficiently reliable procedure since only minor losses of the ozonides and styrene occur from the reaction mixture. The total ozonide yields for the styrenes were similar to literature values[11] and ranged as follows: *p*-methyl 60 ± 10%, unsubstituted 75 ± 15%, *p*-chloro 65 ± 10%, *p*-nitro 35 ± 10%.

Cleavage Direction.—Each styrene (1.0 mmol) was ozonized to the extent of 80% (based on ozone input) in $CDCl_3$ (5 ml) at 0 °C in the presence of methanol (1—2 mmol). The proton n.m.r. methine peaks of the two methoxy hydroperoxides[5,12] were integrated to give the proportions of cleavage in each direction. The averages for 4—8 runs are listed in the Table as the relative cleavage rate coefficients k_a and k_b.

Kinetic Schemes.—In the computer algorithm for Scheme 2 Euler's method was used to approximate the solutions to the kinetic rate equations.[5] The program was written in FORTRAN-77 for a PDP-11/23 computer. Input assumptions were the concentration of the primary ozonide and the added benzaldehyde, based on the reaction stoicheiometry, along with values for the five rate constants (see Scheme 2). After cleavage of the primary ozonide according to k_a and k_b, ozonide yields were calculated for a small consumption of the carbonyl oxides assuming complete scrambling of the carbonyl oxides and aldehydes with their reactivities determined by k_{sb}, k_{st}, and k_{et}. Successive iterations followed after each correction of the reactant concentrations. The calculation was stopped when the calculated ozonide products corresponded to the overall experimental yields. The calculations were repeated for new values of k_{st} and k_{sb} until the best agreement between the calculated and experimental yields were obtained. The algorithm is similar to those recently described for other crossed ozonide studies.[5]

Acknowledgements

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References

1 Recent reviews include: (*a*) P. S. Bailey, 'Ozonation in Organic Chemistry,' Academic Press, New York, 1978, vol. 1; 1982, vol. 2; (*b*) R. L. Kuczkowski, in '1,3-Dipolar Cycloaddition Chemistry,' ed. A. Padwa, Wiley, New York, 1984, vol. 2, ch. 11.

2 (*a*) S. Klutsch and S. Fliszár, *Can. J. Chem.*, 1972, **50**, 2841; (*b*) H. Henry, M. Zador, and S. Fliszár, *ibid.*, 1973, **51**, 3398; (*c*) S. Fliszár and J. Renard, *ibid.*, 1967, **45**, 533; (*d*) S. Fliszár and M. Granger, *J. Am. Chem. Soc.*, 1969, **91**, 3330.

3 H. L. Casal, S. E. Sugamori, and J. C. Scaiano, *J. Am. Chem. Soc.*, 1984, **106**, 7623.

4 H.-S. Choi and R. L. Kuczkowski, *J. Org. Chem.*, 1985, **50**, 901.

5 J.-I. Choe, M. K. Painter, and R. L. Kuczkowski, *J. Am. Chem. Soc.*, 1984, **106**, 2891; J.-I. Choe, M. Srinivasan, and R. L. Kuczkowski, *ibid.*, 1983, **105**, 4703.

6 J. Shorter, 'Correlation Analysis in Organic Chemistry,' Oxford University Press, London, 1973.

7 P. S. Bailey, 'Ozonation in Organic Chemistry,' Academic Press, New York, 1978, vol. 1, p. 89.

8 R. D. Nelson, D. R. Lide, and A. A. Maryott, 'Selected Values of Electric Dipole Moments for Molecules in the Gas Phase,' National Standard Reference Data System – National Bureau of Standards, 1967, 10.

9 J.-S. Su and R. W. Murray, *J. Org. Chem.*, 1980, **45**, 678.

10 S. Fliszár and J. Renard, *Can. J. Chem.*, 1970, **48**, 3002.

11 R. Criegee and H. Korber, *Chem. Ber.*, 1971, **104**, 1807; A.C.S. Advances in Chemistry Series no. 112, 1972, p. 22.

12 J. Renard and S. Fliszár, *Can. J. Chem.*, 1969, **47**, 3333; W. P. Keaveney, M. G. Berger, and J. J. Pappas, *J. Org. Chem.*, 1967, **32**, 1537.

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