OZONOLYSIS. CONCENTRATION AND SOLVENT EFFECTS

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Abstract—The effect of solvent and the effect of olefin concentration on the ozonolysis of *cis* and *trans*-2,5-dimethylhexene-3 have been measured. For both olefin stereoisomers the more nucleophilic solvents give a higher percentage *trans* ozonide. The ozonide stereoisomer ratio changes with concentration at low concentrations but is constant at higher concentrations for both olefin stereoisomers. The significance of these results to the ozonolysis mechanism problem is discussed.

INTRODUCTION

A NUMBER of recent reports have indicated that the ozonolysis reaction is a more complex process than it was previously believed to be.[2-11] These results have placed additional requirements on a mechanistic interpretation of the ozonolysis process. Among the observations requiring further mechanistic explanation are the following: (1) the dependence of ozonide *cis-trans* ratios on olefin stereochemistry,[2, 3, 6-8, 10, 11] (2) the dependence of cross ozonide* *cis-trans* ratios on olefin geometry,[10-12] (3) the dependence of normal and cross ozonide *cis-trans* ratios on steric factors in the olefin,[11] (4) the dependence of ozonide yield on olefin geometry,[2, 8, 10, 11] and (5) solvent effects on the course of ozonolysis.[10]

The fundamental mechanism for the ozonolysis process is the Criegee[13] zwitterion mechanism. Recently, Bailey *et al.*[14] have increased our understanding of the mechanism by demonstrating that, at least in the case of *trans*-1,2-di-t-butylethylene, the initial ozonide has a symmetrical structure, thus eliminating the 4-membered ring structure (I) from consideration. Bailey has suggested that at least in some solvents this symmetrical structure is II, the structure originally proposed by Harries[15] for the normal ozonide and later by Criegee for the initial ozonide.
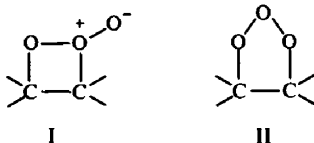
* The two symmetrical ozonides obtained in the ozonolysis of an unsymmetrical olefin are referred to as cross ozonides. The term normal ozonide is used to describe the unsymmetrical or parent ozonide obtained in such a case.

It seems to us, however, that the Criegee mechanism must be modified in a way which will meet the additional requirements imposed by the results listed above. Criegee[16] has pointed out that the zwitterion may exist as *syn* and *anti* forms but he also concluded that stereoisomeric olefins should give the same cleavage products and, hence, the same ratio of ozonides.[16] It has been suggested[17] that stereoisomeric olefins might not in fact give the same distribution of *syn* and *anti* zwitterions and that the variation in ozonide *cis-trans* ratios might be related to this possibility. Leaving aside for the present the question of the integrity of a *syn* or *anti* zwitterion, we have not as yet been able to make use of this possibility to provide a unified explanation of the accumulated experimental data. The possibility that it makes a contribution to the observed results cannot be ruled out, however. We have speculated on a modification to the mechanism which would take some of the factors listed above into account.[11, 18] Such speculation is meant to serve as a working hypothesis until such time as additional experimental investigations point the way to a more complete mechanism. We report here the results of one such investigation as well as a consideration of the effect of these results on the mechanism problem.

Solvent effects

The ozonolysis of *cis* and *trans*-1,2-diisopropylethylene was carried out in four different solvents at the same concentration in order to determine the effect of the solvent on the reaction. In this study a symmetrical olefin was chosen in order to avoid, at least initially, the additional complexities associated with the production of cross ozonides. The results, shown in Tables 1 and 2, indicate a very definite solvent effect on both yield and stereoisomer distribution. In going from pentane to the more polar solvents ethyl acetate and diethyl ether, the percentage *trans* ozonide produced increases substantially for both the *cis* and the *trans* olefin. However, in methylene chloride, a solvent of higher polarity than diethyl ether, or at least of higher dipole moment, there is only a slight increase in the percentage *trans* ozonide for both the *cis* and *trans* olefins.

The effect on the yield is also pronounced, but more complex. For the *cis* olefins the yields are all comparable except in the case of methylene chloride where it is low. For the *trans* isomer the yield improves somewhat in going from pentane to methylene chloride and ethyl acetate, and increases substantially in diethyl ether. In every solvent used, however, the *cis* olefin gives a higher yield than the *trans* olefin in accordance with earlier reports.[2, 8, 10, 11] Greenwood[10] has also reported that *trans* isomers give higher yields in ether solvents. In the cases of hexene-3 and butene-2, however, Greenwood found that the *cis* isomers gave slightly higher yields in hydrocarbon solvents whereas the ozonolysis of *cis*-1,2-diisopropylethylene reported here gives about the same yield in pentane and ether.

The effect on the ozonide stereoisomer ratio is interesting in that it does not appear to be directly related to the polarity of the solvent used since methylene chloride did not have the same effect as ethyl acetate and diethyl ether. Greenwood has found similar results and has suggested that the dependence may be on the nucleophilicity rather than the polarity of the solvent.[10] Both Greenwood[19] and Bailey[20] had earlier suggested that nucleophilic solvents can react with the molozonide. In the case of reactive solvents, such as methanol, such reactions would lead to diversion of the molozonide to hydroperoxides.[19, 20] In other cases, such as ethers, the solvent would

simply assist in the rearrangement of the molozonide to the ozonide.[19] We have suggested[11, 16] that aldehyde molecules may also cause decomposition of the mol-ozonide leading to a transitory intermediate which can undergo an aldehyde inter-change reaction to give either a normal or cross ozonide. It is felt that such a process would give ozonide *cis-trans* ratios which may be affected by the geometry and substitutents in the starting olefin. The reactions referred to, that is, with methanol, diethyl ether, or aldehydes may represent specific examples from a broad spectrum of related, assisted decompositions of the molozonide.

The results obtained can be rationalized in terms of the mechanistic speculation given earlier.[11, 18] The increase in percent *trans* ozonide from both *cis* and *trans* olefins in more nucleophilic solvents probably indicates more fragmentation of the molozonide and thus ozonide *cis-trans* ratios which are more the result of fragment recombination. The fragment recombination could be a zwitterion–carbonyl process or something more complex. Such a process might be expected to favor production of *trans* ozonide.

A firm correlation of ozonide *cis-trans* ratios with solvent nucleophilicity or polarity cannot be established until data from a greater variety of solvents are available. While the present data suggest that solvent polarity may not be the most important factor in determining ozonide *cis-trans* ratios this conclusion is based on a comparison of dipole moments only. There are a number of more comprehensive parameters which rank solvents according to polarity.[21–23] By choosing solvents from one or more of these classifications it may be possible to more adequately determine the dependence of ozonide *cis-trans* ratio on solvent polarity.*

Concentration effects

Using pentane as solvent a series of solutions of *cis* and *trans* 1,2-diisopropylethylene of varying concentration were ozonized and analyzed for ozonide yield and stereo-isomer distribution. The results for the stereoisomer distribution are shown in Fig. 1. Over a fairly extensive concentration range the ozonide stereoisomer distribution is constant but different for each of the olefin stereoisomers. For the *trans* isomer this constant value is 57:43 (c:t) and is observed at concentrations greater than 2·0 molar. For the *cis* isomer the ratio is 66:34 (c:t) and is true for concentrations above ca. 1·0 molar. Below these concentrations this ratio changes with concentration for both isomers. In the *trans* case the ratio changes in favor of a higher percentage *trans* isomer until about $\frac{1}{16}$ molar where it appears to have a maximum and then goes to a lower percentage *trans* isomer at more dilute concentrations. The total amount of ozonide obtained under these very dilute conditions is very small and the resulting error in the ozonide percentage values is about ±0·5 %. Even allowing for the effect of this limit of error, however, it still seems certain that the curve goes through a maximum. In the case of the *cis* isomer, concentrations below 1·0 molar show a continuous increase in the percentage *trans* ozonide produced. In fact the infinite dilution values for the *cis* and *trans* isomers appear to be approaching one another. Because of the importance of this observation to the mechanism problem we have attempted to examine this concentration range in more detail. To date, however, we find that we are not able to obtain reliable ozonide *cis-trans* ratios below $\frac{1}{128}$ molar.

* We are grateful to Prof. J. A. Berson for this suggestion and for helpful discussions of this problem.

We are now attempting a new approach to the problem of high dilution ozonide stereoisomer ratios.

The effect of concentration on total ozonide yield was also determined and these results are shown in Fig. 2. Here again it can be clearly seen that the *cis* isomer gives
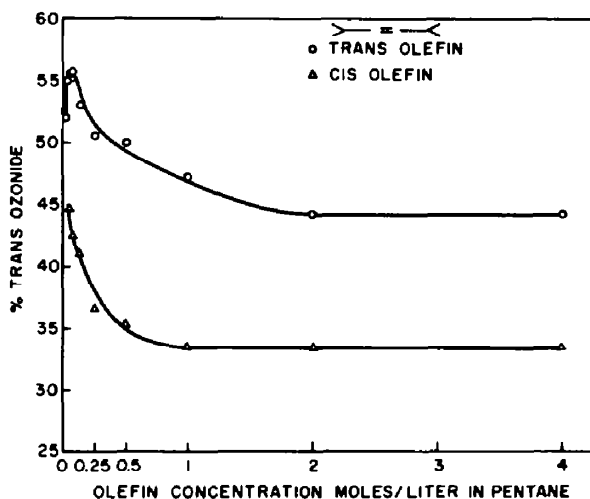

FIG. 1 The percentage *trans* ozonide obtained from *cis* and *trans*-1,2-diisopropylethylene as a function of concentration.
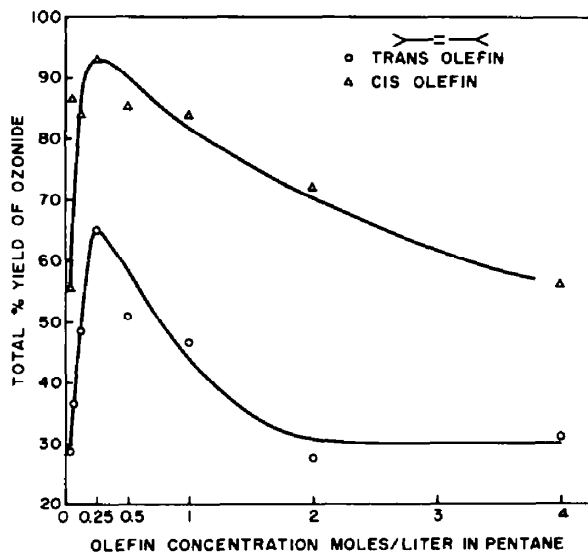

FIG. 2 Ozonide yield as a function of concentration for *cis* and *trans*-1,2-diisopropylethylene.

a higher percentage yield than the *trans* at all concentrations measured. In both cases the yield varies with concentration increasing to a maximum at ca. $\frac{1}{4}$ molar concentration and then falling off sharply with increased dilution.

These results on the effect of concentration on the ozonolysis reaction are of major significance to the mechanism problem. They illustrate again that the ozonide *cis-trans* ratio is a function of olefin stereochemistry and that this is true over a large

TABLE 1. OZONIDE STEREOISOMERS FROM *trans*-1,2-DIISOPROPYLETHYLENE

Solvent	Solvent dipole Moment (Debye units)	Ozonide %		Total yield of ozonides (%)
		trans	*cis*	
Pentane	0	47·3	52·7	46·8
CH$_2$Cl$_2$	1·55	50·8	49·2	55·6
EtOAc	1·81	64·5	35·5	57·4
ET$_2$O	1·15	64·7	35·3	73·1

TABLE 2. OZONIDE STEREOISOMERS FROM *cis*-1,2-DIISOPROPYLETHYLENE

Solvent	Solvent dipole Moment (Debye units)	Ozonide %		Total yield of ozonides (%)
		trans	*cis*	
Pentane	0	34·0	66·0	83·8
CH$_2$Cl$_2$	1·55	36·9	63·1	57·7
EtOAc	1·81	46·6	53·4	81·2
ET$_2$O	1·15	44·3	55·6	84·1

concentration range. More importantly, they demonstrate that there must be more than one mechanism for ozonide formation. Establishing the nature of these mechanisms is a more difficult problem, however. While there are probably several explanations possible for the data, we are presently inclined toward the following general scheme.

There must be at least two pathways contributing to the ozonide *cis-trans* ratios for both olefin stereoisomers. One of these pathways is dominant at very low concentrations, but is soon overwhelmed by another pathway which continues to be dominant over a large concentration range, hence the constant ozonide *cis-trans* ratio. The first pathway may be the Criegee zwitterion–carbonyl recombination pathway which could give the same ozonide *cis-trans* ratio for both olefin isomers. Unfortunately at the moment we cannot say with certainty that this is true, but only that the ozonide *cis-trans* ratios appear to be approaching one another. The possibility that one or more other pathways are available in this very dilute region cannot be excluded.

As the concentration increases a new major pathway becomes increasingly important and finally becomes dominant. This pathway is apparently more sensitive to olefin stereochemistry and leads to the constant ozonide *cis-trans* ratio difference

between the olefin stereoisomers. Because of the concentration dependence it seems reasonable to postulate that this dominant pathway is bimolecular in nature. Possible pathways include the reaction of two olefin-ozone adducts or that of one such adduct with an aldehyde molecule as suggested earlier.[11, 18] The ozonide yield dependence is probably also related to the mechanism situation. The existing data suggest that the dominant pathway tends to reduce the ozonide yield from the optimum value at ca. $\frac{1}{4}$ molar until a fairly constant value is reached. This may be because this pathway while able to grossly influence the ozonide *cis-trans* ratio is also one which permits nonozonide-producing reactions to occur.

The data here permit one to say with a greater degree of certainty that there is more than one pathway to ozonide formation. The data further suggest that there may be a high dilution pathway which is the same for *cis* and *trans* olefin isomers.

EXPERIMENTAL

The GLPC analyses were carried out on an Aerograph Model A-700 Gas Chromatograph using a 10 ft, 10% cyanosilicone column and equipped with an Aerograph Model 471 Digital Integrator.

Ozonolyses. The general procedure described earlier[11] was used. All ozonolyses were conducted at ca. −70° and continued to 75% of the theoretical amount of ozone required. All varying concentration runs were carried out in pentane. Each of the ozonide *cis-trans* ratios reported represents an average of at leat four or, for those at high dilution, at least six determinations. The runs in methylene chloride, ethyl acetate, diethyl ether, and pentane for the solvent effect determination were all done in 1·0 molar solutions.

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