Ozonolysis of *cis-* and *trans-*Diisopropylethylene in the Presence of ^{18}O-Labeled Isobutyraldehyde

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Ozonolysis of *cis-* and *trans-*diisopropylethylene in the presence of ^{18}O-labeled isobutyraldehyde leads to incorporation of the ^{18}O label in both the ether and peroxide bridges of the resulting diisopropylozonide. More of the ^{18}O label is incorporated in the peroxide bridge at lower temperatures.

We have recently shown[2] that ozonolysis temperature has an important effect on ozonide isomer ratio and yield. These results are important to the problem of the mechanism of ozonolysis, since they contain support for an additional mechanism for the reaction which we had suggested earlier.[3,4] According to our earlier suggestion, under suitable reaction conditions the initial olefin–ozone adduct **3** (Scheme I) might react directly with the aldehyde to give **10** and eventually ozonide **13** with an isomer ratio which differs from that produced in the accompanying Criegee[5] zwitterion pathway **3** → **8** → **14**.

The use of ^{18}O-labeled aldehyde in principle permits one to distinguish the two reaction pathways described. Thus the pathway through a partially cleaved initial adduct **6** eventually places the ^{18}O only in the peroxide, whereas the Criegee pathway places the ^{18}O only in the ether bridge of the final ozonide, **14**.

In some early work[6] it was found that, in the case of *trans-*diisopropylethylene ozonized at low temperature in the presence of ^{18}O-labeled acetaldehyde, a sizable amount of the ^{18}O label is found in the peroxide bridge of the methylisopropylozonide product. In this case the location of the label was determined by chemical means.

Fliszár and coworkers[7-9] have also used the ^{18}O-labeling technique and have concluded that, in the ozonolysis of phenylethylenes in the presence of ^{18}O-labeled benzaldehyde, the ^{18}O label is incorporated exclusively in the ether bridge. In this work, mass spectrometry was used to determine the location of the label. It should also be noted that most of these ozonolyses were carried out at room temperature.[9] These workers also felt that the simple Criegee pathway was inadequate[10] and suggested an alternative path to ozonide formation, **3** → **2** → **11** → **14**, which places the ^{18}O label in the ether bridge.

For the sake of completeness, Scheme I contains all possible structures **2**, **3**, **4**, and **5** for the initial adduct. In fact, structure **3** is now considered the preferred structure except in those cases of hindered 1 olefins in which **5** seems to be the most likely structure.[11] Scheme I also includes an alternative form **7** of a partially cleaved initial adduct as well as indicating that the zwitterion pathway may include both cage and solvated possibilities.

Results and Discussion

The results obtained from mass spectrometric analysis of diisopropyl ozonides produced by ozonolysis of 0.2 *M* solutions of *cis-* and *trans-*diisopropylethylene in the presence of varying concentrations of ^{18}O-labeled isobutyraldehyde are given in Table I. It should be noted that separate results were obtained for the cis and trans ozonide in order to obtain the maximum amount of information regarding the total mechanism. The total labeling was obtained from the molecular ion peaks 160 and 162. The labeling of the ozonides in the ether bridge was derived from the peaks at *m/e* 128 and 130, assuming the loss of two oxygen atoms (mass 32 or 34) occurs only from the peroxide bridge. In this connection, it is important to note that loss of methyl groups is not important, leading to small peaks at M − 15 and M − 30. The errors reported in Table I are calculated for the 90% confidence limit. The ^{18}O-labeling was calculated as follows.

$$\%\ \text{labeling} = 100\,\frac{\dfrac{H\,(\mathrm{M}+2)}{H\,(\mathrm{M})} - \dfrac{H_0\,(\mathrm{M}+2)}{H_0\,(\mathrm{M})}}{1 + \dfrac{H\,(\mathrm{M}+2)}{H\,(\mathrm{M})} - \dfrac{H_0\,(\mathrm{M}+2)}{H_0\,(\mathrm{M})}}$$

The index zero refers to unlabeled ozonide and *H* corresponds to the peak heights at the given *m/e* ratio. The labeling of the ozonides in the peroxide bridge is calculated as the difference between the total ^{18}O-labeling and the labeling in the ether bridge.

As shown in Table I, considerable amounts of ^{18}O-labeled aldehyde are incorporated into the ozonide at both ends of the temperature range of interest. Furthermore, ^{18}O is definitely incorporated into the peroxide bridge and more ^{18}O is incorporated into the peroxide bridge at the lower temperatures for both the cis and trans olefins. These results are thus compatible with the conclusions reached earlier[6] in a similar system where the ^{18}O distribution was determined by chemical methods.

Two significant differences distinguish the Fliszár, *et al.*, work[7-9] and that reported here. All of the olefins studied by Fliszár, *et al.*, contain an aromatic substituent at the double bond. In these cases, the phenyl group would be expected to stabilize the zwitterion thus favoring this reaction pathway. Second, and perhaps more important, the lowest temperature studied by these workers was −78°[7] with most of the ozonolysis to

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[1] Ciba Photochemical, Ltd., Fribourg, Switzerland. The work was carried out at Bell Telephone Laboratories, Inc., Murry Hill, N. J.

[2] R. W. Murray and R. Hagen, *J. Org. Chem.*, **36**, 1098 (1971).

[3] R. W. Murray, R. D. Youssefyeh, and P. R. Story, *J. Amer. Chem. Soc.*, **89**, 3143 (1966).

[4] R. W. Murray, R. D. Youssefyeh, and P. R. Story, *ibid.*, **89**, 2429 (1967).

[5] R. Criegee, *Rec. Chem. Progr.*, **18**, 111 (1957).

[6] P. R. Story, C. E. Bishop, J. R. Burgess, R. W. Murray, and R. D. Youssefyeh, *J. Amer. Chem. Soc.*, **90**, 1907 (1968).

[7] S. Fliszár, J. Carles, and J. Renard, *ibid.*, **90**, 1364 (1968).

[8] S. Fliszár and J. Carles, *ibid.*, **91**, 2637 (1969).

[9] J. Castonguay, M. Bertrand, J. Carles, S. Fliszár, and Y. Rousseau, *Can. J. Chem.*, **47**, 919 (1969).

[10] S. Fliszár and M. Granger, *J. Amer. Chem. Soc.*, **92**, 3361 (1970).

[11] R. W. Murray, *Accounts Chem. Res.*, **1**, 313 (1968).

SCHEME I

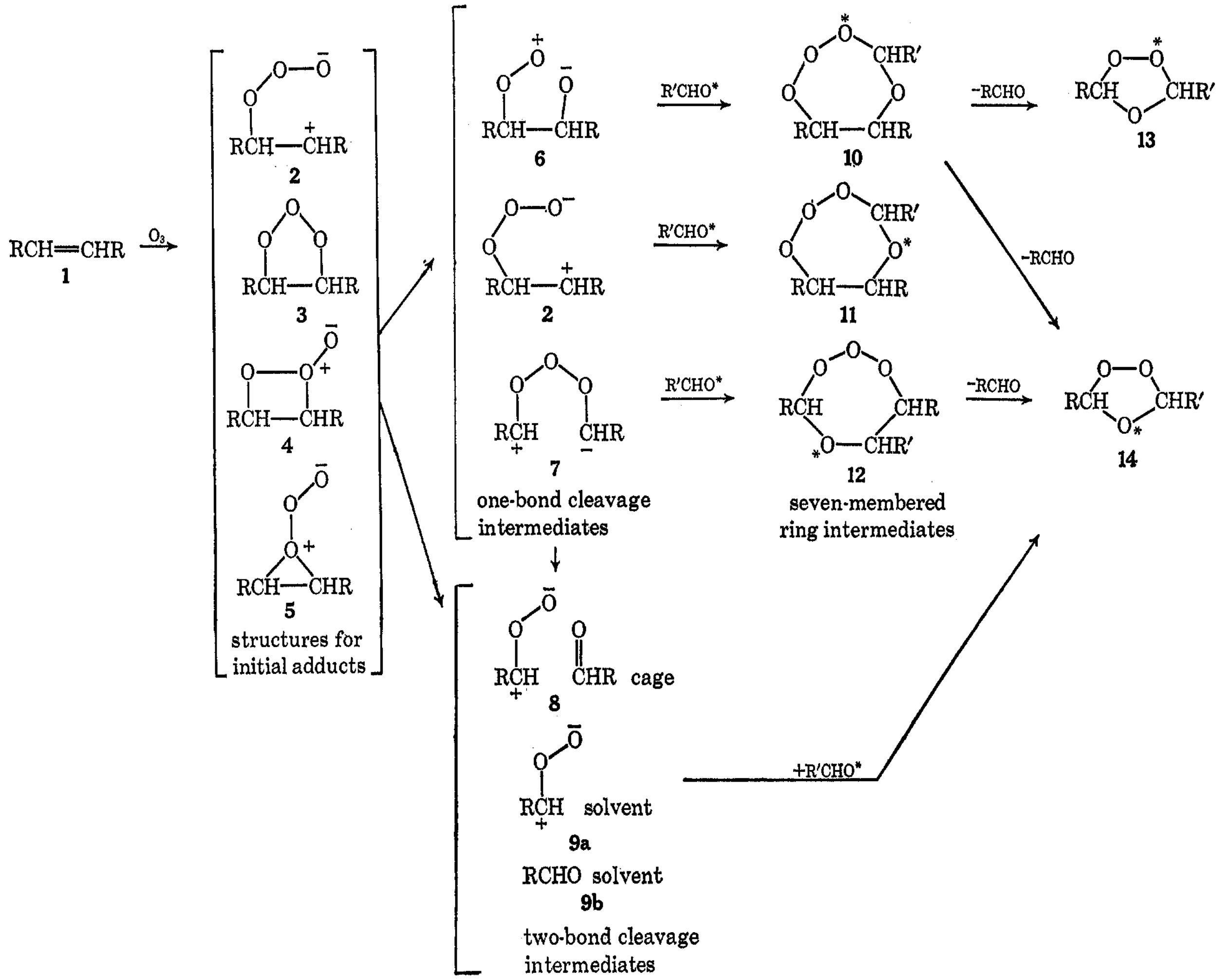
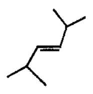
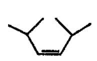


TABLE I

MASS SPECTROMETRIC RESULTS FOR ^{18}O-LABELED DIISOPROPYL OZONIDES[a,b]

Olefin	Aldehyde concn, mol/l.	Ozonization temp, °C	Warm-up	Total ^{18}O labeling, %		^{18}O labeling in the ether bridge, %		^{18}O labeling in the peroxide bridge, %	
				Cis ozonide	Trans ozonide	Cis ozonide	Trans ozonide	Cis ozonide	Trans ozonide
	0.2	−117	Slow	11.4 ± 1.1	18.8 ± 1.4	11.0 ± 1.8	12.2 ± 1.0	0.4 ± 2.1	6.6 ± 1.6
		−117	Fast	22.2 ± 0.8	25.9 ± 1.4	18.2 ± 4.4	14.3 ± 3.3	4.0 ± 4.5	11.6 ± 3.6
		−1	Fast	23.0 ± 0.8	25.8 ± 0.8	19.2 ± 0.9	22.2 ± 1.9	3.8 ± 1.2	3.6 ± 2.0
	1.0	−122	Fast	22.0 ± 0.3	24.0 ± 1.6	16.2 ± 2.6	11.3 ± 0.7	5.8 ± 2.6	12.7 ± 1.8
	0.2	−118	Slow	18.8 ± 1.4	16.9 ± 0.6	15.3 ± 1.2	1.7 ± 0.7	3.5 ± 1.8	15.2 ± 0.9
		−113	Fast	17.8 ± 1.5	17.1 ± 1.0	13.6 ± 1.3	6.8 ± 1.5	4.2 ± 1.9	10.3 ± 1.8
		−1	Fast	20.2 ± 1.3	20.2 ± 0.8	15.6 ± 1.4	16.4 ± 2.6	4.6 ± 1.9	3.8 ± 2.7
	0.4	−120	Fast	17.3 ± 1.8	18.3 ± 0.4	17.2 ± 1.6	7.6 ± 1.6	0.1 ± 2.4	10.7 ± 1.6

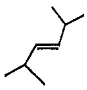
[a] Obtained by ozonolysis of 0.2 *M* solutions of *cis*- and *trans*-diisopropylethylene in the presence of ^{18}O-labeled isobutyraldehyde. Errors are given for the 90% confidence limit. [b] ^{18}O enrichment of the aldehyde was 34% for the experiments at 0.2 *M* aldehyde concentration and 22% in the other cases.

give ^{18}O-labeled ozonides being carried out at *room temperature.*[9] The mechanism we have suggested,[3,4] permitting ^{18}O incorporation in the peroxide bridge, gives a role to the initial adduct and thus would be expected to be more significant at lower temperatures. The results in Table I are at least consistent with this expectation. It may be significant that Fliszár, *et al.*,[7] considered that up to 10% ^{18}O incorporation in the peroxide bridge at the lowest temperature used (−78° for *cis*-stilbene and −20° for *trans*-stilbene) would be consistent with their data. However, the stilbene ozonide obtained from the ozonolysis of styrene in the presence of ^{18}O-labeled benzaldehyde at −78° was labeled exclusively in the ether position. The extension of ^{18}O-labeling studies to lower temperatures for olefins with aromatic substituents should perhaps be completed before a final conclusion concerning the mechanism is made for these cases.

In agreement with the results found in ref 2, solutions of the trans olefin ozonized at low temperature show less incorporation of bulk aldehyde on slow warm-up than on fast warm-up. For the trans olefin, also, fast warm-up at low temperatures leads to a greater incorporation of ^{18}O into the peroxide bridge than slow warm-up, with the trans ozonide receiving about two-thirds of the total. For the cis olefin, with its less stable initial adduct,

TABLE II

RANGES FOR THE ^{18}O LABELING IN THE ETHER BRIDGE (IN PER CENT OF THE TOTAL LABELING) AND FOR THE OZONIDE CIS/TRANS RATIOS FOR LABELING IN THE ETHER BRIDGE AND LABELING IN THE PEROXIDE BRIDGE[a]

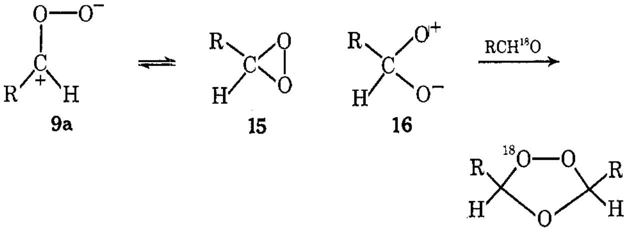
				Most probable ranges of the ^{18}O labeling in the ether bridge in % of total labeling		Most probable ranges of the ozonide cis/trans ratios		
Olefin	Aldehyde concn, mol/l.	Ozonization temp, °C	Warm-up	Cis ozonide	Trans ozonide	Total ozonide	Ozonide labeled in the ether bridge	Ozonide labeled in the peroxide bridge
	0.2	−117	Slow	74 to 100	55 to 76	52/48	43/57 to 55/45	0/100 to 35/65
		−117	Fast	60 to 100	40 to 72	34/66	29/71 to 51/49	0/100 to 35/65
		−1	Fast	77 to 91	76 to 96	35/65	29/71 to 35/65	20/80 to 63/37
	1.0	−122	Fast	61 to 87	41 to 54	44/56	47/53 to 58/42	15/85 to 38/62
	0.2	−118	Slow	70 to 95	6 to 15	74/26	94/6 to 98/2	23/77 to 51/49
		−113	Fast	64 to 91	29 to 52	73/27	80/20 to 88/12	34/66 to 66/34
		−1	Fast	66 to 90	66 to 98	56/44	49/51 to 61/39	35/65 to 88/12
	0.4	−120	Fast	82 to 100	32 to 51	70/30	80/20 to 88/12	0/100 to 39/61

[a] Obtained from ozonolyses of 0.2 *M* solutions of *cis*- and *trans*-diisopropylethylene in pentane in the presence of isobutyraldehyde enriched in ^{18}O.

both fast and slow warm-up at low temperature lead to sizable amounts of ^{18}O being incorporated into the peroxide bridge. Here again the trans ozonide receives a greater percentage of the total.

The experiments at 0.4 and 1.0 *M* aldehyde concentrations were carried out to investigate the importance of the different labelings at high aldehyde concentration. These data are important to an interpretation of the relative labeling in the ether and peroxide bridges since it is at least conceivable, although probably not very likely, that some ^{18}O could be incorporated into the peroxide bridge as shown in Scheme II.

SCHEME II



If this scheme were an important source of ^{18}O labeling in the peroxide bridge, then it would be expected to play a reduced role at higher aldehyde concentrations where there is greater opportunity for interception of **9a** prior to equilibration through **15** and **16**. In fact, the relative importance of peroxide and ether bridge labeling does not change greatly with aldehyde concentration, although one does observe a higher incorporation of bulk aldehyde. It is significant also that Fliszár and coworkers[12] have demonstrated in an elegant way that structure **16** does not participate in the mechanism of ozonide formation in the ozonolysis of *trans*-4-methyl-2-pentene.

Table II gives the mass spectral data in a form which is perhaps more suitable for a discussion of the mechanisms leading to cross ozonide. It contains the labeling in the ether bridge as a percentage of the total labeling and estimated ranges for the ozonide cis/trans ratios for both ether and peroxide bridge labeled material. The ranges given are estimated to be the most probable values and were calculated from the data in Table I by taking the extreme cases of the 90% confidence limits.

At an aldehyde concentration of 0.2 *M*, the label went to about two-thirds or more into the ether bridge of the cis ozonide for all reaction conditions. In the trans ozonide, the label is also placed preferentially in the ether bridge in the ozonolyses at high temperatures.

However, for the trans ozonide at low temperature, the labeling in the peroxide bridge becomes more important for both cis and trans olefins and, in the case of the cis olefin, even becomes dominant.

From the ranges reported in Table II for the cis/trans ratios of the ozonide labeled in the ether bridge, it appears that the cis and trans olefins are giving different cis/trans cross ozonide ratios at all temperatures, the cis olefin giving a higher percentage of cis ozonide and both olefins tending toward a higher percentage of cis ozonide at lower temperatures. The ozonide with labeling in the peroxide bridge contains a larger percentage of trans ozonide in the case of the trans olefin while the cis olefin can give a higher percentage of cis ozonide.

Summary and Conclusions

It has been shown that ozonolysis of *cis*- and *trans*-diisopropylethylene in the presence of ^{18}O-labeled isobutyraldehyde leads to incorporation of the ^{18}O label at both the ether and the peroxide bridge of the resulting disopropylozonide. The incorporation of the ^{18}O label in the peroxide bridge is temperature dependent with more of this labeling occurring at lower temperatures. These results are consistent with our earlier suggestion[3,4] that ozonide formation by the Criegee zwitterion pathway may be accompanied by an additional pathway involving reaction of the initial adduct **3** with aldehyde.

In the simplest interpretation, the per cent labeling in the ether bridge could be taken as the percentage contribution of the Criegee zwitterion pathway. The peroxide bridge labeling would then indicate the percentage contribution of some other pathway, possibly the aldehyde–initial adduct pathway. On this basis, for the trans olefin, the Criegee zwitterion pathway is most important (80%) at −1° with fast warm-up. Its lowest contribution (60%) is at −122°, fast warm-up and high added aldehyde concentration. For the cis olefin, maximum influence of the zwitterion path is also observed at −1° (79.5%) and fast warm-up, while the

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[12] G. Klutsch, J. Grignon, J. Renard, and S. Fliszár, *Can. J. Chem.*, **48**, 1598 (1970).

lowest contribution (60%) of this path was observed at −113° and fast warm-up.

According to the working hypothesis suggested earlier by us,[3,4] operation of the path **6** → **10** → **13** should give relatively more cis ozonide from the cis olefin than from the trans olefin. As yet there does not appear to be a way to put this prediction on an absolute basis.

The results shown in Tables I and II indicate that if cis and trans olefins are compared under the same conditions, then in all cases studied the cis olefin gives relatively more cis ozonide in the nonzwitterion pathway. In the other cases studied, which are not directly comparable, the trans olefin with 1.0 *M* added aldehyde and at −122° gives more cis ozonide than the cis olefin at 0.4 *M* added aldehyde at −120°. In this last comparison, the cis olefin gives very little cis ozonide contrary to the stereochemical predictions made earlier.[3,4]

While the relative ozonide cis/trans ratios observed are consistent in most cases with the predictions previously made,[3,4] the differences are small and cannot be regarded as substantiating these predictions. In all cases except one (−1°) the trans ozonide incorporates more ^{18}O labeling than the cis ozonide. It is difficult to go from these data to an absolute ozonide cis/trans ratio for the nonzwitterion pathway. The most probable ranges are given in Table II. These ranges do not permit any definite statement on the stereochemical course of the additional reaction pathway.

Experimental Section

The ozonolysis and analytical procedures have been described.[2]

Preparation of ^{18}O-Labeled Isobutyraldehyde.—Isobutyraldehyde and ^{18}O-labeled water (YEDA, normalized in hydrogen) were mixed and kept at room temperature for several days. The water was separated from the aldehyde on a 10 ft by 1/4 in. column filled with 80–100 Poropak W (He flow rate 1–6 ml/sec, column temperature 135°). Minor impurities, such as acids, were removed from the aldehyde by means of a 30 ft by 3/8 in. column containing 5% XF-1150 on Chromosorb G (He flow rate 10 ml/sec, column temperature 57°). Two lots of different ^{18}O labeling were prepared. Aldehyde, 34% enriched in ^{18}O, was used for the experiments with 0.2 *M* aldehyde concentration, whereas the experiments with 0.4 and 1.0 *M* aldehyde concentrations were carried out with isobutyraldehyde, 22% enriched in ^{18}O. The percentage enrichment was determined from mass spectra.

Preparation of ^{18}O-Labeled Ozonides.—The ^{18}O-labeled diisopropylethylene ozonides were produced by ozonizing 0.2 *M* solutions of *cis*- or *trans*-diisopropylethylene in pentane in the presence of varying concentrations of ^{18}O-labeled isobutyraldehyde. Ozonolysis was carried out to 50% conversion in a procedure similar to that described for the unlabeled aldehyde experiments.

Mass Spectra of the Diisopropylethylene Ozonides.—The mass spectra were run on a Consolidated Electronics Corporation Model 21-104 mass spectrometer. Since the ozonides decompose at an appreciable rate above *ca.* 80°, it was necessary to vaporize the samples at room temperature. The source temperature was 165° and the ion voltage was set at 70 V. Under these conditions, the molecular ion peak was quite stong, but by no means the strongest signal. The most intense lines were at *m/e* 43, 41, 72, and 56. Above 73 the most intense line was at *m/e* 117 (M − 43), which corresponds to a fragment where the molecular ion has lost an isopropyl group.

The intensities of the mass peaks in the region important for this investigation are given below (relative to the molecular peak intensity = 100).

	Relative intensities of mass peaks (*m/e*)							
	162	161	160	159	130	129	128	127
Cis ozonide	1.1	8.7	(100)	1.7	0.12	0.39	2.78	2.48
Trans ozonide	1.1	8.8	(100)	3.4	0.18	0.78	6.57	3.72

These intensities were obtained as an average of several mass spectra traces of unlabeled diisopropylethylene ozonides. The peaks at *m/e* 158 and 126 were negligible and the peaks at *m/e* 145 (M − 15) and 144 (M − 16), which correspond to fragments produced from the molecular ion by loss of a methyl group or an oxygen atom, were generally much smaller than the peak at *m/e* 128. In some cases the peaks at *m/e* 145 and 128 were of the same order of magnitude. The relative intensities of the peaks at *m/e* 127 and 128 were rather characteristic for the two ozonide isomers although they varied occasionally for no obvious reason.

The total ^{18}O labeling of the ozonides was calculated from the *m/e* peaks at 160 and 162 and the labeling in the ether bridge was determined from the peaks at *m/e* 128 and 130, taking into account the relative peak intensities $I(162)/I(160)$ and $I(130)/I(128)$ obtained from the unlabeled ozonides. Generally two separate gpc collections from the same ozonolysis were analyzed with the mass spectrometer for each isomer with three traces taken for each collection. Since no obvious differences between two analogous collections were obtained, the average of all six traces was calculated and reported in Table I. Sometimes the amounts of ozonide available were so small that the two collections had to be combined for the mass spectral analysis and in these cases six traces were taken. The errors were calculated for the 90% confidence limits. They do not include possible errors due to relative intensity variations of $I(162)/I(160)$ and $I(130)/I(128)$ for unlabeled samples.

The labeling in the peroxide bridge was calculated by difference and assuming that the following formula applies.

$$S^2 = S_1^2 + S_2^2$$

Registry No.—*cis*-Diisopropylethylene, 10557-44-5; *trans*-diisopropylethylene, 692-70-6; ^{18}O-labeled isobutyraldehyde, 27720-65-6.

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