

# Superoxide Chemistry. Reactions of Superoxide with Alkyl Halides and Alkyl Sulfonate Esters

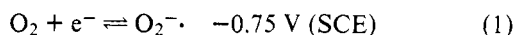
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**Abstract:** The main peroxidic product obtained from the reaction of  $\text{KO}_2$  with primary  $\text{R-X}$  in benzene, in DMF, and in  $\text{Me}_2\text{SO}$  and from reaction with secondary  $\text{R-X}$  in benzene is the dialkyl peroxide,  $\text{R-O-O-R}$ . The reaction of  $\text{KO}_2$  with secondary  $\text{R-X}$  in DMF gives both hydroperoxide,  $\text{R-O-O-H}$ , and dialkyl peroxide. The reaction of  $\text{KO}_2$  with secondary  $\text{R-X}$  in  $\text{Me}_2\text{SO}$  gives alcohol,  $\text{R-O-H}$ . Elimination reactions occur with all secondary substrates, giving olefins as byproducts. These results are consistent with the mechanism outlined in eq 2-5 wherein the initial reaction is a nucleophilic displacement of  $\text{X}$  by  $\text{O}_2^{\cdot-}$  to give an intermediate alkylperoxy radical. Electron transfer from superoxide to this radical rapidly converts the latter to an alkylperoxy anion. Reaction of this peroxy anion with  $\text{R-X}$ , with  $\text{H}_2\text{O}$  (during the reaction quench), or with  $\text{Me}_2\text{SO}$  can lead to dialkyl peroxide, alkyl hydroperoxide, or alcohol, respectively.

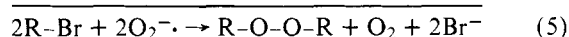
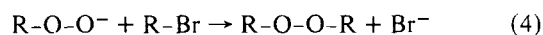
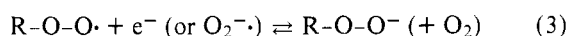
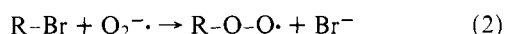
Synthetic applications of the superoxide radical anion,  $\text{O}_2^{\cdot-}$ , in organic systems were not extensively studied before 1975.<sup>1</sup> The fact that superoxide was most commonly available as the alkali metal salts, sodium superoxide ( $\text{NaO}_2$ ) and potassium superoxide ( $\text{KO}_2$ ),<sup>2</sup> made application to organic chemistry difficult because of the lack of solubility in the organic system. Attempts to explore both the radical and the ionic nature of  $\text{O}_2^{\cdot-}$  with suspensions of  $\text{KO}_2$  in benzene or tetrahydrofuran met with limited success.<sup>3</sup> Examination of electron transfer from  $\text{O}_2^{\cdot-}$  to various organic molecules by using  $\text{KO}_2$  in dimethyl sulfoxide was somewhat more successful.<sup>4</sup>

A second approach to the study of superoxide reactions in organic systems has been based on the electrochemical generation of  $\text{O}_2^{\cdot-}$  from oxygen.<sup>5</sup> In this method,  $\text{O}_2^{\cdot-}$  is generated at the cathode in an organic medium according to the equation



The electrolyte is usually a quaternary ammonium salt in these reactions and acts as the counterion to the superoxide ion. Various solvents, such as dimethylformamide, dimethyl sulfoxide, acetonitrile, acetone, pyridine, and methylene chloride, have been used in these reactions.

A notable application of the electrochemical method to an organic reaction was reported by two groups in 1970.<sup>6,7</sup> Superoxide was found to react with alkyl halides to form dialkyl peroxides or alkyl hydroperoxides. After a detailed electrochemical study of the reaction, Dietz and co-workers proposed the sequence of reactions shown in eq 2-5 as being consistent with their experimental results.<sup>6</sup> An initial  $\text{S}_{\text{N}}2$  displacement of bromide by superoxide was suggested (eq 2). This was followed by rapid electron transfer from the electrode or from superoxide to the peroxy radical to give the peroxy anion (eq 3). Formation of the dialkyl peroxide product (eq 4) was proposed to be the result of a second  $\text{S}_{\text{N}}2$  displacement reaction. The overall reaction also results in the production of a 0.5 equiv of oxygen.



Since 1975, reports of the reaction of superoxide with organic molecules have become more frequent,<sup>1</sup> stimulated in part by the use of crown ethers<sup>8-12</sup> to solubilize the alkali metal superoxides and in part by the use of the more soluble salt tetramethylammonium superoxide.<sup>13,14</sup>

The synthetic potential of the aforementioned preparation of dialkyl peroxides stimulated our interest in superoxide, since we had as one of our objectives the synthesis of the prostaglandin endoperoxide,  $\text{PGH}_2$ . This report describes the details of the synthetic method that we have developed for the synthesis of dialkyl peroxides using model compounds. We also consider the mechanisms that may be involved as reflected by the product analyses of these reactions.


## Discussion

The preparation of dialkyl peroxides from the reaction of alkyl bromides or mesylates with superoxide<sup>6</sup> appeared to have considerable potential as a synthetic route. As an experimentally simpler alternative to the electrochemical method of generating superoxide, we considered the possibility of solubilizing one of the alkali metal salts of superoxide in organic solvents by adding a crown ether to the medium. In our first experiments, potassium superoxide was stirred overnight in dimethylformamide (DMF), tetrahydrofuran (THF), or benzene, each containing 1 equiv of both dicyclohexyl-18-crown-6 and 2-bromooctane. Examination of the reaction mixtures by thin layer chromatography<sup>15</sup> (TLC) clearly showed that one and the same peroxide had been formed in each experiment. Because of the ease of workup and also because it represented the greatest extreme in solvent nonpolarity, benzene was chosen as the solvent for further study of this reaction. The results of all individual experiments (or runs) that we have done are summarized in Table I. Unless otherwise specified, yields for all products except olefins are based on amounts of the products actually isolated.

The reactions of several primary bromoalkanes with  $\text{KO}_2$  were examined first to determine the general character of the reaction and to develop a convenient synthetic routine. These experiments are represented by runs 1-7 (Table I) and show that simple primary dialkyl peroxides can be produced in yields of 50-70% by this method. From observation of the reactions in benzene, we conclude that the time required for completion of the reaction depends upon the rate of dissolution of the solid  $\text{KO}_2$  into the reaction medium. The preceding reactions all were run with crown ether present in an amount equivalent to the molar concentration of the bromoalkane. When 0.1 equiv of crown ether was used (run 8), the reaction proceeded as before but required a slightly longer time to reach completion. When no crown ether (run 9) was added to the reaction, the bromoalkane remained unchanged for 114 h.

In order to examine the reaction with primary bromoalkanes more carefully, several runs (10-14) were made using long-chain bromoalkanes. The products from these substrates have the advantage of being crystalline. From either 1-bromohex-

Table I. Reactions of R-X with KO<sub>2</sub><sup>a</sup>

run	solvent <sup>b</sup> (mL)	substrate, R-X (mmol)	KO <sub>2</sub> , mmol	crown ether, <sup>c</sup> mmol	rxn time, h	O <sub>2</sub> ↑, mmol	ROOR, %	ROOH, %	ROH, %	olefins, %	carbonyl, %	other, %
1	Bz (15)	1-C <sub>5</sub> H <sub>11</sub> Br (10)	10	10	20		53					
2	Bz (15)	1-C <sub>6</sub> H <sub>13</sub> Br (10)	10	10	5		47					
3	Bz (15)	1-C <sub>6</sub> H <sub>13</sub> Br (10)	10	10	3		50					
4	Bz (15)	1-C <sub>6</sub> H <sub>13</sub> Br (10)	10	10	4		54					
5	Bz (15)	1-C <sub>6</sub> H <sub>13</sub> Br (10)	10	10	3		71					
6	Bz (15)	1-C <sub>7</sub> H <sub>15</sub> Br (10)	10	10			56					
7	Bz (15)	1-C <sub>8</sub> H <sub>17</sub> Br (5)	5	5	3	2.3	68		8			
8	Bz (15)	1-C <sub>6</sub> H <sub>13</sub> Br (10)	10	0	114 <sup>d</sup>		0					
9	Bz (15)	1-C <sub>6</sub> H <sub>13</sub> Br (10)	10	1	24		50					
10	Bz (15)	1-C <sub>16</sub> H <sub>33</sub> Br (4)	5	1	18		49		21			ether, 8
11	Bz (15)	1-C <sub>18</sub> H <sub>37</sub> Br (5)	5	5	20		47					
12	Bz (15)	1-C <sub>18</sub> H <sub>37</sub> Br (5)	5	5	7		55		15			
13	Bz (15)	1-C <sub>18</sub> H <sub>37</sub> Br (5)	5	5	6		77		21			
14	Bz (15)	1-C <sub>18</sub> H <sub>37</sub> Br (5)	5	5	6	2.5	54		16	3	0	ether, 4
15	Bz (15)	1-C <sub>18</sub> H <sub>37</sub> Br (5)	5	5	24		61		18			
16	Tol (15)	1-C <sub>18</sub> H <sub>37</sub> Br (5)	5	5	7		50		15			
17	THF (15)	1-C <sub>18</sub> H <sub>37</sub> Br (5)	5	5	5		52		7			
18	Bz (15)	1-C <sub>18</sub> H <sub>37</sub> OTs (5) <sup>e</sup>	9.7	5	40		50		42			
19	Bz (15)	1-C <sub>18</sub> H <sub>37</sub> OMs (5) <sup>f</sup>	6.9	5	25.5		46		40			
20	Bz (10)	(1-C <sub>18</sub> H <sub>37</sub> O) <sub>2</sub> (1)	4.5	2	48				48			
21	Bz (15)	 Br (5)	5.3	5	5	2.1	50					
22	Bz (15)	2-C <sub>8</sub> H <sub>17</sub> Br (10)	10.7	10	5		49	8		37		
23	Bz (15)	c-C <sub>6</sub> H <sub>11</sub> Br (10)	10	10	20					67		
24	Bz (15)	c-C <sub>5</sub> H <sub>9</sub> Br (10)	10	10	5		42			24		
25	Bz (10)	2-C <sub>8</sub> H <sub>17</sub> OTs (5) <sup>g</sup>	5.4	5	7		52		14	16		
26	Bz (15)	2-C <sub>8</sub> H <sub>17</sub> OMs (5) <sup>h</sup>	6.8	5			44		19	14		
27	Me <sub>2</sub> SO (20)	1-C <sub>5</sub> H <sub>11</sub> Br (3.3)	10	1	1.25		41					
28	Me <sub>2</sub> SO (25)	1-C <sub>8</sub> H <sub>17</sub> Br (7)	21	7	0.5	3.2	48	0	21			Me <sub>2</sub> SO <sub>2</sub> , 0
29	Me <sub>2</sub> SO (20)	1-C <sub>8</sub> H <sub>17</sub> Br (3.3)	10	1	1.25		68		19		1.5	
30 <sup>i</sup>	Me <sub>2</sub> SO (30)	1-C <sub>18</sub> H <sub>37</sub> Br (5)	16.5	1.65	1.5		44	23	22			
31	Me <sub>2</sub> SO (30)	1-C <sub>18</sub> H <sub>37</sub> OTs (5)	16.5	1.65	2.5		4	32	39			
32	Me <sub>2</sub> SO (30)	1-C <sub>18</sub> H <sub>37</sub> OTs (5)	16.5	1.65	1.5		7	35	44			
33	Me <sub>2</sub> SO (12)	2-C <sub>7</sub> H <sub>15</sub> Br (2)	6	2	1		0	0	56	33		Me <sub>2</sub> SO <sub>2</sub> , 65
34	Me <sub>2</sub> SO (12)	2-C <sub>7</sub> H <sub>15</sub> Br (2)	6	2	1.5	0.7	0	0	56	34		Me <sub>2</sub> SO <sub>2</sub> , 63
35	Me <sub>2</sub> SO (12)	2-C <sub>8</sub> H <sub>17</sub> OTs (2)	6	2	1.5	0	0	0	66		0	
36	Me <sub>2</sub> SO (12)	2-C <sub>8</sub> H <sub>17</sub> OTs (2)	6	2	1.5	0			71	12		
37	Me <sub>2</sub> SO (12)	2-C <sub>8</sub> H <sub>17</sub> OTs (2)	6	2	1.5	0			71	14		Me <sub>2</sub> SO <sub>2</sub> , 73
38	DMF (20)	1-C <sub>8</sub> H <sub>17</sub> Br (5)	15	5	0.2	2.5	48	4	21			
39	DMF (15)	1-C <sub>18</sub> H <sub>37</sub> OTs (3)	15	1	5		11	39	17			
40	DMF (20)	2-C <sub>7</sub> H <sub>15</sub> Br (5)	15	5	0.2	2.7	19	31		36		
41	DMF (20)	2-C <sub>8</sub> H <sub>17</sub> Br (5)	15	5	0.6		29	32				
42	DMF (100)	2-C <sub>8</sub> H <sub>17</sub> Br (25)	75	25	0.5		20	32				

<sup>a</sup> Details of the experimental methods are provided in the Experimental Section. <sup>b</sup> Bz = benzene, Tol = toluene, THF = tetrahydrofuran, Me<sub>2</sub>SO = dimethyl sulfoxide, DMF = dimethylformamide. <sup>c</sup> Dicyclohexyl-18-crown-6 was used in all experiments except runs 15, 29, 41, and 42, wherein 18-crown-6 was used. <sup>d</sup> The concentration of 1-bromohexane remained constant for the length of the experiment. <sup>e</sup> V. C. Sekera and C. S. Marvel, *J. Am. Chem. Soc.*, **55**, 345 (1933). <sup>f</sup> See ref 28. <sup>g</sup> A. Streitwieser, Jr., T. D. Walsh, and J. R. Wolfe, *J. Am. Chem. Soc.*, **87**, 3682 (1965). <sup>h</sup> H. A. Weiner and R. A. Sneen, *ibid.*, **87**, 287 (1965). <sup>i</sup> Unreacted 1-bromooctadecane (37%) was recovered in this experiment and yields are corrected for this recovery.

adecane (run 10) or 1-bromooctadecane (run 14), small quantities of ethers were obtained in addition to peroxide and alcohol. 1-Octadecene was also detected in the reaction of 1-bromooctadecane with KO<sub>2</sub>. No other minor products were detected in these reactions.

18-Crown-6 (run 15) and dibenzo-18-crown-6 both were useful in solubilizing KO<sub>2</sub>, although the latter compound was itself sparingly soluble in benzene (product detected by TLC in this case). Toluene and tetrahydrofuran were also satisfactory as solvents for the reaction (runs 16 and 17).

Most of the primary dialkyl peroxides produced in these reactions have been reported previously in the chemical literature. In our work, these products (except for di-*n*-octadecyl peroxide) have been characterized by their response to the ferrous thiocyanate spray reagent<sup>15</sup> and by their NMR spectra. Of particular interest in the NMR spectra of these compounds

are the signals for the protons on the carbon α to the peroxide oxygens. The positions of these signals are summarized in Table II and are compared with the signals of other compounds likely to be found in these reactions, i.e., the starting alkyl bromides, the related ethers, and the corresponding alcohols. The signals for the methylene protons α to peroxide oxygen clearly are at lower field (δ 3.95) than are those of the other possible structures. Di-*n*-octadecyl peroxide was further characterized by its mass spectrum having fragments at *m/e* 523 (M<sup>+</sup> - CH<sub>3</sub>) and 269 [CH<sub>3</sub>(CH<sub>2</sub>)<sub>17</sub>O]<sup>+</sup>.

1-Octadecanol tosylate (run 18) and mesylate (run 19) were each allowed to react with KO<sub>2</sub> in benzene. Again the dialkyl peroxide was the main reaction product, indicating that these sulfonate esters also were suitable substrates for the reaction. The relatively large quantities of alcohol formed in these two reactions are related to the fact that more than 1 equiv of KO<sub>2</sub>

**Table II.** NMR Signals on Carbon  $\alpha$  to Peroxide Oxygen Compared to Other Methylene Protons

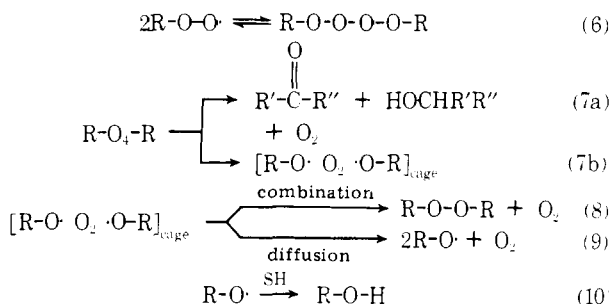
RCH <sub>2</sub>	RCH <sub>2</sub> OOC- H <sub>2</sub> R <sup>a</sup>	RCH <sub>2</sub> Br <sup>b</sup>	RCH <sub>2</sub> OC- H <sub>2</sub> R <sup>b</sup>	RCH <sub>2</sub> OH <sup>b</sup>
C <sub>5</sub> H <sub>11</sub>	3.96 (CDCl <sub>3</sub> )	3.33 (CCl <sub>4</sub> )	3.38 (CDCl <sub>3</sub> )	3.50 (CDCl <sub>3</sub> )
C <sub>6</sub> H <sub>13</sub>	3.97 (CDCl <sub>3</sub> )	3.38 (CCl <sub>4</sub> )	3.29 (CCl <sub>4</sub> )	3.50 (CCl <sub>4</sub> )
C <sub>7</sub> H <sub>15</sub>	3.96 (CDCl <sub>3</sub> )	3.33 (CCl <sub>4</sub> )		3.50 (CCl <sub>4</sub> )
C <sub>16</sub> H <sub>33</sub>	3.97 (CDCl <sub>3</sub> )	3.35 (CCl <sub>4</sub> )	3.40 (CDCl <sub>3</sub> )	
C <sub>18</sub> H <sub>37</sub>	3.95 (CDCl <sub>3</sub> )	3.30 (CCl <sub>4</sub> )	3.38 (CDCl <sub>3</sub> )	3.59 (CDCl <sub>3</sub> )

<sup>a</sup> Determined in present work. <sup>b</sup> Obtained from Sadtler, "Standard NMR Spectra", Sadtler Research Laboratories, Inc.

was required to ensure complete consumption of starting material. As noted in the following paragraph, KO<sub>2</sub> slowly converts dialkyl peroxides into alcohols.

The ability of KO<sub>2</sub> to react further with dialkyl peroxides was examined briefly. Di-*n*-octadecyl peroxide in benzene containing dicyclohexyl-18-crown-6 reacted slowly with excess KO<sub>2</sub> (run 20). 1-Octadecanol (48%) was isolated from the reaction after the starting peroxide was completely consumed. The fate of the material left unaccounted for is unknown as yet. This experiment clearly suggests that dialkyl peroxides are susceptible to slow reduction to, at least in part, the corresponding alcohol. This observation may explain the presence of alcohol as byproduct in many of the reactions run in benzene.

An alternate explanation is possible for the formation of alcohols in these reactions and is found in the free-radical reaction pathways available to the alkylperoxy radicals generated by eq 2. The key steps in these pathways are summarized in eq 6–10.<sup>16</sup> Alcohols emerge from this scheme via both eq 7a and



eq 10. Although alkoxy radicals have been trapped from the reactions under discussion here,<sup>17</sup> there are several observations that suggest that the above scheme does not play an important role. First, as discussed here, dialkyl peroxides clearly are the major reaction products in benzene whereas in the literature describing the above free-radical pathways, dialkyl peroxides are seldom seen in yields greater than 5%.<sup>18,19</sup> Second, Dietz and coworkers estimated that the electron transfer step (eq 3) of their mechanism occurred at or near a diffusion-controlled rate ( $k_2 \approx 10^9 \text{ M}^{-1} \text{ s}^{-1}$ )<sup>6</sup> whereas the fastest self-reaction rate for the radical pathways (observed for primary systems) is on the order of  $2k_1 \approx 3 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$ .<sup>16a</sup> Third, eq 7a of the above scheme predicts formation of aldehydes or ketones as reaction products; these are products we have not observed in our reactions. Fourth, and finally, reaction of 1-bromo-4-pentene (run 21) with KO<sub>2</sub> will give as an intermediate the unsaturated alkylperoxy radical **1**, which has available to it

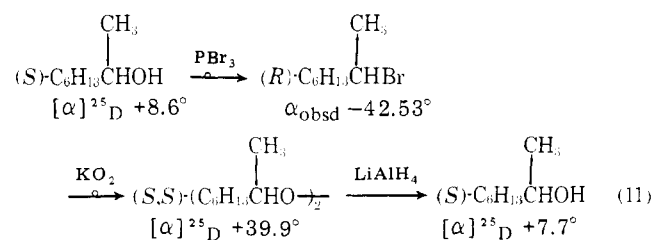


further reaction either by eq 2 leading to di-4-pentenyl peroxide or by intramolecular cyclization to **2**, an intermediate that may trap oxygen to give a cyclic peroxide-hydroperoxide such as described by Porter and co-workers.<sup>18d,e</sup> The only peroxidic material detected and isolated from this reaction is the dialkyl peroxide (see Table I). From these considerations we conclude that radical pathways are not important to the formation of alcohols in the reactions of KO<sub>2</sub> with alkyl halides and alkyl sulfonate esters in benzene.

Extension of the reaction to secondary substrates was of interest to us because (a) our ultimate substrate was a 9,11-dibromoprostaglandin in which the reactive sites would be secondary and (b) now competition from elimination reactions may become important. Reaction of 2-bromooctane (run 22) with KO<sub>2</sub> in benzene does give significant amounts of olefins which we presume to arise via an elimination mechanism. The main product of the reaction is the dialkyl peroxide, however. Three olefinic isomers (1-octene, *trans*-2-octene, and *cis*-2-octene) may be expected from the elimination reaction and all three were detected as based on GLC retention times. Separation of the three isomers was incomplete, so it was only possible to estimate the composition as being 60% *trans*-2-octene and 40% of a mixture of *cis*-2-octene and 1-octene. A major product in this reaction (run 22) was sensitive to ferrous thiocyanate spray but was more polar than di-2-octyl peroxide. These properties and the NMR spectrum were consistent with assignment of 2-octyl hydroperoxide as the structure of this product.

The cyclic secondary bromide, cyclohexyl bromide, was very susceptible to elimination (run 23), cyclohexene being present in the product to the extent of 67% as determined by GLC. Peroxide was detected in this reaction by TLC, but was not isolated. Changing the solvent for the reaction from benzene to DMF reduced the amount of elimination somewhat, but cyclohexene was still formed in the amount of 50%. Fortunately, elimination from cyclopentyl bromide was significantly reduced (run 24) relative to cyclohexyl bromide. Only 24% of cyclopentene was detected by GLC and the isolated yield of dicyclopentyl peroxide was 42%.

The stereochemistry of the carbon-oxygen bond forming reaction at secondary carbon was examined next. The mechanism proposed by Dietz and co-workers requires two S<sub>N</sub>2 reactions.<sup>6</sup> Consequently, inversion of configuration at secondary carbon may be expected if this is the mechanism by which the reaction proceeds. Optically active 2-bromooctane was prepared by reaction of (*S*)-2-octanol with phosphorus tribromide according to the procedure of Hudson.<sup>20</sup> This reaction is known to occur with essentially complete inversion at the asymmetric center when the reaction is allowed to reach only 1/3 completion. The (*R*)-2-bromooctane so obtained (eq 11) was then converted to di-2-octyl peroxide. Reduction of



the latter with lithium aluminum hydride, a reaction known to proceed with retention of configuration,<sup>21</sup> gave (*S*)-2-octanol. The entire reaction sequence proceeded with a net 94% retention of configuration, so we conclude that the formation of the peroxide must proceed with inversion at the asymmetric carbon.

The secondary sulfonate esters 2-octanol tosylate (run 25) and 2-octanol mesylate (run 26) also proved to be satisfactory

**Table III.** Change in Me<sub>2</sub>SO<sub>2</sub> Concentration with Time in Solutions of KO<sub>2</sub> in Me<sub>2</sub>SO<sup>a</sup>

time, h	Me <sub>2</sub> SO <sub>2</sub> concn, mol/L	time, h	Me <sub>2</sub> SO <sub>2</sub> concn, mol/L
0.25	0.0224	3.75	0.0328
0.5	0.0169	4.25	0.0408
0.5	0.0221	4.75	0.0318
0.75	0.0206	6.0	0.0432
0.75	0.0238	25	0.0378
1.0	0.0199	53	0.0615
1.25	0.0306	72	0.0660
1.75	0.0259	95	0.0735
2.0	0.0399	120	0.0915
2.25	0.0392	124	0.0863
2.75	0.0294	141	0.0915
3.0	0.0316	170	0.1150

<sup>a</sup> These results combine data from three independent runs of this control experiment.

substrates for reaction with KO<sub>2</sub>. The extent of elimination observed with these two substrates was significantly less than with 2-bromooctane, although the amount of peroxide obtained was not enlarged correspondingly. 2-Octanol was also isolated as a minor product of these reactions and, since optically active alcohol was used to prepare the tosyl and mesyl esters, it became possible to determine the stereochemistry involved. The alcohol formed in both of the reactions was of opposite configuration relative to starting material (see Experimental Section for details of specific rotations), indicating an inversion at the asymmetric center during the reaction.

With the exceptions of runs 20 and 21, we had completed the experiments described above<sup>10</sup> when the communications of first San Filippo, Chern, and Valentine<sup>9</sup> and then of Corey and his colleagues<sup>11</sup> appeared. Under conditions that varied from ours only in the choice of solvent and in the use of excess KO<sub>2</sub>, these two groups reported that alcohols were the main products obtained from the reaction of KO<sub>2</sub> with primary and secondary alkyl halides and alkyl sulfonate esters. Both groups used dimethyl sulfoxide (Me<sub>2</sub>SO) in the reaction medium.

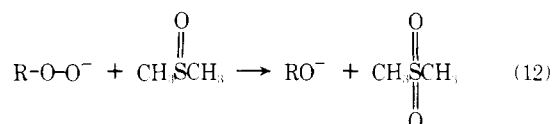
Because of the apparent sensitivity of the reaction to changes in conditions, we reexamined the reaction of KO<sub>2</sub> with several substrates in Me<sub>2</sub>SO.<sup>22</sup> To our surprise, we were able to detect and isolate dialkyl peroxides as the main product from the reaction of KO<sub>2</sub> with either of the primary alkyl bromides, 1-bromopentane (run 27) and 1-bromooctane (run 28). Under conditions that duplicated those of San Filippo and co-workers<sup>9</sup> (run 29), dioctyl peroxide was detected by GLC as the main reaction product from 1-bromooctane and KO<sub>2</sub>. Care must be taken to determine the stability of the peroxide to the column condition when analyzing these reactions by GLC.

Reaction of long-chain substrates with KO<sub>2</sub> in Me<sub>2</sub>SO gave mixtures of peroxide, hydroperoxide, and alcohol (runs 30–32). Rationalization of the results of these three experiments is complicated by the fact that the substrates, as well as some of the products, are not completely solubilized under the reaction conditions used.

The secondary substrates 2-bromooctane and 2-octanol tosylate reacted with KO<sub>2</sub> in Me<sub>2</sub>SO to give 2-octanol as the main product. Peroxides, both the dialkyl peroxide and the hydroperoxide, were detected immediately after the reaction was started but these products did not persist. Since the peroxides were not present at the time that the reactions were worked up, these reactions were analyzed by GLC techniques. Considerably more elimination to form olefins (34% vs. 14%) was observed when 2-bromooctane (runs 33 and 34) was the substrate than when 2-octanol tosylate (runs 35–37) was the substrate.

The possibility that an intermediate peroxy radical (via eq 2) or peroxy anion (eq 3) is reacting with the Me<sub>2</sub>SO to pro-

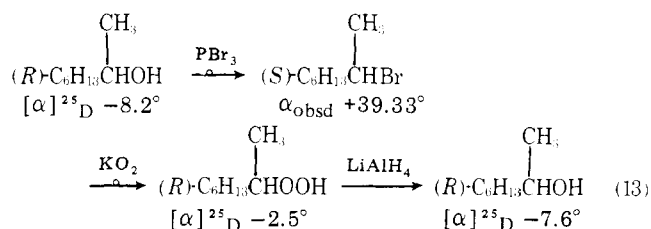
duce an alcohol and dimethyl sulfone (Me<sub>2</sub>SO<sub>2</sub>) was considered. Indeed, Gibian and Ungermann have shown that *tert*-butylperoxy anions react rapidly with Me<sub>2</sub>SO to form *tert*-butyl alcohol and Me<sub>2</sub>SO<sub>2</sub>.<sup>23</sup> We have analyzed examples of each of the reactions that we have done in Me<sub>2</sub>SO for the presence of Me<sub>2</sub>SO<sub>2</sub>. The reactions of primary substrates, from which we isolated dialkyl peroxides, did not produce any Me<sub>2</sub>SO<sub>2</sub> (run 28). On the other hand, Me<sub>2</sub>SO<sub>2</sub> was produced in all the reactions of the secondary substrates (runs 33, 34, 37). Furthermore, the quantity of Me<sub>2</sub>SO<sub>2</sub> produced was approximately equal to the amount of alcohol formed in these reactions. These results are consistent with the occurrence in these reactions of the step represented by eq 12.



In a series of control experiments, summarized in Table III we found that KO<sub>2</sub> itself reacts only slowly with Me<sub>2</sub>SO relative to the rates of the preceding reactions.

We have also studied these reactions using dimethylformamide (DMF) as the solvent. Just as in Me<sub>2</sub>SO, reaction of 1-bromooctane with KO<sub>2</sub> in DMF (run 38) gave di-*n*-octyl peroxide as the main product plus smaller amounts of 1-octanol and 1-hydroperoxyoctane. The long-chain substrate 1-octadecanol tosylate (run 39) gave a mixture of peroxide, hydroperoxide, and alcohol in which the hydroperoxide predominated. Again, these results are similar to those observed for the same reaction when run in Me<sub>2</sub>SO. Two secondary bromides, 2-bromoheptane (run 40) and 2-bromooctane (runs 41 and 42), were used as substrates for the reaction in DMF. Both gave mixtures of peroxide, hydroperoxide, and olefin as products. An observation incidental to these reactions in DMF is the fact that in the absence of substrate, the KO<sub>2</sub> will slowly (2–3 days) react with the DMF. We have not examined this reaction other than to observe a distinct amine (dimethylamine?) odor after the KO<sub>2</sub> is consumed.

The stereochemistry of formation of the 2-hydroperoxyoctane formed in run 42 was examined and is summarized in eq 13. The complete sequence proceeded with a net 96% retention



of configuration. Consequently, formation of the carbon-oxygen bond of the hydroperoxide must occur with inversion of configuration.

In several of the experiments listed in Table I, we have measured the volume of gas released during the reactions with KO<sub>2</sub>. We assume that the gas being released is oxygen. In every reaction examined except one (runs 35–37), the amount of oxygen released is near or equal to 0.5 equiv relative to the amount of substrate used for the reaction. This observation is consistent with the pathway proposed by Dietz and co-workers. The fate of the oxygen in one exception, the reaction of KO<sub>2</sub> with 2-octanol tosylate, has not been determined.

In summary, the reactions described here provide a convenient synthesis of dialkyl peroxides. The yields of primary dialkyl peroxides obtained by this method are comparable with, and in some cases better than, those reported for the generally used peroxide syntheses.<sup>25</sup> Yields of secondary dialkyl peroxides, except for the cyclohexyl example, are better than those

obtained by other methods. A further benefit of the present procedure is the relative simplicity and ease with which it may be performed. With respect to use of this method for the conversion of alkyl halides and sulfonate esters to alcohols, we have found it useful only with secondary substrates when the reaction is performed in dimethyl sulfoxide. An alternate approach to alcohol synthesis is found in the hydride reduction of the dialkyl peroxides to alcohols.

Our results are consistent with the basic mechanistic scheme proposed by Dietz and colleagues.<sup>6</sup> This scheme is outlined above by eq 2-4. As noted before, the first step of this scheme requires a nucleophilic displacement reaction as the carbon-oxygen bond-forming step. Our stereochemical results are consistent with such a displacement reaction. Superoxide should not be capable of reacting with alkyl halides or alkyl sulfonate esters by an alternate electron transfer mechanism. The oxidation potential of  $O_2^{\cdot-}$  must be about 0.75 V (vs. SCE). Since the reduction potential for primary alkyl bromides is about -2.3 V and for alkyl sulfonate esters is about -2.9 V,<sup>26,27</sup> the superoxide radical anion falls short by -1.5 to -2.1 V of the energy needed for the reaction to proceed by electron transfer.

Perhaps the key intermediate in the mechanistic scheme of Dietz and colleagues is the peroxy anion formed as a result of the electron-transfer step of eq 3. Reaction of this peroxy anion with R-X, with water (during the reaction quench), or with  $Me_2SO$  leads to dialkyl peroxide, alkyl hydroperoxide, or alcohol (plus dimethyl sulfone), respectively. Which of these pathways is followed depends further upon both the solvent used for the reaction and whether the substrate is a primary or secondary alkyl halide (or sulfonate ester). In benzene, dissolution of  $KO_2$  into the medium apparently is so slow that the concentration of peroxy anion remains small relative to R-X. As a result, dialkyl peroxides are the major products isolated from the reaction of  $KO_2$  with either primary or secondary R-X in benzene.

In  $Me_2SO$  and DMF, the solubility of  $KO_2$  is sufficiently high so that the concentration of peroxy anion is no longer limited by superoxide concentration. Now competition between the rates of reaction of R-X with superoxide and with peroxy anion controls the outcome of the reaction. We conclude that in these solvents the primary peroxy anions again react more rapidly with R-X than does superoxide since the major products are dialkyl peroxides. With secondary compounds in these solvents, the reaction of the peroxy anion with R-X must be either comparable to or slower than the reaction of superoxide with R-X, since little or no dialkyl peroxide is formed. In  $Me_2SO$ , the peroxy anion then reacts with solvent to form alcohol and dimethyl sulfone while in DMF it remains in solution until converted to the hydroperoxide by aqueous quenching of the reaction.

## Experimental Section

**General.** Potassium superoxide used in these experiments was purchased from the Ventron Corp., Beverly, Mass. Dicyclohexyl-18-crown-6 (Du Pont) was a mixture of stereoisomers and was a solid at room temperature. The 18-crown-6 (PCR, Inc.) used was a crystalline solid.

The yields of peroxide, alcohol, and aldehyde in run 28 were determined using a Hewlett-Packard Model 5700A chromatograph with a flame ionization detector. The column was a 34 in.  $\times$  3 mm (i.d.) glass coil loaded with 10% OV-1 on 80-100 mesh G.H.P. The column temperature was held at 100 °C for 8 min, then increased at a rate of 32 °C/min to 250 °C and held at 250 °C for 16 min. Di-*n*-octyl peroxide gave reproducible peaks at 12.0 and 21.6 min under these conditions.

The yields of olefins and of alcohols (where TLC showed the absence of peroxide or hydroperoxide) were also determined by GLC techniques. All the conditions described below resulted in partial or complete decomposition of dialkyl peroxides to alcohols and ketones or aldehydes. Therefore, care must be taken in analyzing these reac-

tions in order to avoid erroneous measurements of product yields. An F and M Scientific Model 5750 research chromatograph equipped with a flame ionization detector was used. A Hewlett-Packard Model 3373B integrator was used for quantitation. The general technique used was to compare the integrated peak areas for the reaction samples to those of standard samples containing the expected products at a concentration equal to 100% of the theoretical yield of that product. The control samples were injected and analyzed immediately before and/or after the reaction samples were analyzed. In this way the area of the sample peak/area of control peak  $\times$  100 gave directly the percent yield. The yields of olefins for runs 33, 34, 36, 37, and 40 and the yields of alcohols for runs 33, 34, 36, and 37 were determined with a 6 ft stainless steel column packed with 3% Silar SCP on 80-100 mesh Gas Chrom Q; the column temperature was increased from 100 to 250 °C at a rate of 8 °C/min. The yields of olefins for runs 22-26, 36, and 37 and the yield of alcohol for runs 36 and 37 were determined with a 3 ft stainless steel column packed with 26.6% Carbowax 20M on 70-80 mesh Gas Chrom Z; the column temperature was held for 4 min at 90 °C and then increased from 90 to 225 °C at a rate of 8 °C/min.

Preparation and characterization of the following peroxides have been described in the literature: di-*n*-pentyl peroxide, di-*n*-hexyl peroxide, and di-*n*-heptyl peroxide, all in ref 28.

**General Procedure for Reaction of Alkyl Halides or Sulfonate Esters with Potassium Superoxide in the Presence of Dicyclohexyl-18-crown-6. A. In Benzene.** Potassium superoxide (Ventron, 0.375 g of 95% quality = 0.356 g, 0.0050 mol) is weighed directly into a dry 50-mL Erlenmeyer flask containing a cylindrical 1-in. magnetic stirring bar. Benzene (15 mL, dried by azeotropic removal of water) is added to the flask as soon as possible. The alkyl bromide or sulfonate ester (0.0050 mol) is then added to the mixture. Dicyclohexyl-18-crown-6 (1.86 g, 0.0050 mol) is added to the mixture. After the crown ether has dissolved (several minutes) the pieces of potassium superoxide are carefully crushed using a heavy glass stirring rod. The resulting mixture is protected from moisture with a calcium chloride drying tube and is stirred with a magnetic stirring motor. The initial yellow color of the powdered potassium superoxide often is seen to gradually disappear and a white precipitate (presumably potassium bromide) appears. The course of the reaction may be followed by thin layer chromatography (TLC).<sup>15</sup>

If the reaction mixture no longer contains any yellow potassium superoxide but still has some unreacted starting material, additional potassium superoxide may be added and stirring continued. Using the conditions described above, the initial superoxide generally was consumed within 3-6 h. (If any large pieces escaped crushing, these may remain intact longer than this time.)

The reaction mixture is worked up by pouring into saturated aqueous sodium chloride solution (75 mL) and extracting with benzene or methylene chloride (3  $\times$  50-75 mL). The latter is preferred with long-chain products. The aqueous phase will be slightly to moderately alkaline. The organic phase is dried ( $MgSO_4$ ), filtered, and concentrated under reduced pressure. The residue is chromatographed on a silica gel column (100 g) packed as a slurry in benzene and the products may be eluted with benzene. In this way, the dialkyl peroxides are eluted early in the chromatography. Alternatively, the residue may be chromatographed on a silica gel column (100 g) packed as a slurry in 5% methylene chloride in Skellysolve B.

In the present experiments the weight yields of the noncrystalline dialkyl peroxides obtained after chromatography were corrected for the presence of solvent by the NMR spectra of the products. The principal contaminant of the product was the benzene used for the chromatography and the yields were corrected accordingly. Yields of crystalline products were determined in the usual way. Results of the individual experiments are summarized in Table I.

**B. In Dimethyl Sulfoxide.** Potassium superoxide (1.58 g, 21 mmol) is weighed directly into a 100-mL flask and covered immediately with dry (over molecular sieves) dimethyl sulfoxide (25 mL). The  $KO_2$  is carefully crushed. Dicyclohexyl-18-crown-6 (0.75-2.6 g, 2-7 mmol) is added to the mixture which is stirred for 15-30 min at room temperature. The alkyl halide or sulfonate ester (7 mmol) is added, either neat or in  $Me_2SO$  solution. The reaction proceeds quite rapidly with foaming (release of  $O_2$ ) and is slightly exothermic. Cooling of the reaction vessel may be used, but is not required for the reaction size described here. After 30-90 min the reaction mixture is worked up by the careful addition of brine (100 mL, saturated aqueous sodium chloride) to destroy the excess  $KO_2$ , followed by extraction with methylene chloride (four times). The extract is dried and can be

chromatographed as described in part A, above.

**C. In Dimethylformamide.** The procedure used is similar to that described above for  $\text{Me}_2\text{SO}$ . For an example, see the preparation of (*R*)-(-)-2-hydroperoxyoctane described in a following paragraph.

**Formation and Measurement of Dimethyl Sulfone ( $\text{Me}_2\text{SO}_2$ ) in Reactions Carried Out in Dimethyl Sulfoxide ( $\text{Me}_2\text{SO}$ ).** The presence and quantity of  $\text{Me}_2\text{SO}_2$  in control samples and in runs 24, 29, and 30 was determined by GLC using a 6-ft column packed with 3% Silar 5 CP on 80–100 mesh Gas Chrom Q. The column was either programmed to increase in temperature from 100 to 275 °C at a rate of 8 °C/min (for samples of the reactions) or was used at a 180 °C isotherm for analysis of samples used to determine the rate of  $\text{Me}_2\text{SO}$  oxidation by  $\text{KO}_2$ .

In mixtures of  $\text{KO}_2$  (0.427 g, 0.0060 mol) and  $\text{Me}_2\text{SO}$  (12.0 mL) containing dicyclohexyl-18-crown-6 (0.75 g, 0.0020 mol), the change in concentration of  $\text{Me}_2\text{SO}_2$  with time was observed as summarized in Table III. It should be noted that under the conditions of this control reaction an excess of  $\text{KO}_2$  is present as a solid during the reaction. It is presumed that this ensures a constant concentration of  $\text{KO}_2$  near the saturation point for the conditions described.

In contrast to the slow increase in the concentration of  $\text{Me}_2\text{SO}_2$  seen in the results of Table III, when the substrates of runs 29 and 30 were added to identically prepared  $\text{KO}_2$ - $\text{Me}_2\text{SO}$  solution mixtures, the concentration of  $\text{Me}_2\text{SO}_2$  increased to 0.107 and 0.122 mol/L, respectively, within 1 h.

**Reaction of 1-Bromohexadecane with Potassium Superoxide. Di-*n*-hexadecyl Peroxide and Other Products.** This reaction was completed before the general procedure above was completely worked out and so is slightly different in some aspects. Using 0.0050 mol of reactants, the mixture was stirred at room temperature for 24 h. It was then partially concentrated under reduced pressure after which 5% (v/v) methylene chloride in Skellysolve B was added and the resulting mixture was placed directly on a column of silica gel (100 g) that had been packed as a slurry in 5%  $\text{CH}_2\text{Cl}_2$ -SSB. The column was eluted with the same solvent mixture, collecting fractions of 25-mL volume. Fractions 3–10 contained recovered 1-bromohexadecane (0.229 g, infrared spectrum identical with that of an authentic sample).

Fractions 14–52 contained 0.362 g (0.000 733 mol, 44% based on recovered starting material) of crystalline material, mp 47–48 °C. Recrystallization from acetone gave colorless crystals of **di-*n*-hexadecyl peroxide**, mp 47–48 °C (lit.<sup>29</sup> mp 44–46 °C).

Fractions 53–63 contained 0.081 g (~10%) of a crystalline mixture of peroxide and ether.

Fractions 64–80 contained 0.025 g (3%) of crystalline di-*n*-hexadecyl ether, mp 53–54 °C. Recrystallization from acetone gave colorless crystals, mp 53–54 °C (lit.<sup>30</sup> mp 55–56 °C).

Fractions 116–252 contained 0.166 g (21%) of a semicrystalline product, whose infrared spectrum is identical with that of 1-hexadecanol.

**Reaction of 1-Bromooctadecane with Potassium Superoxide. Di-*n*-octadecyl Peroxide and Other Products.** The general procedure described above was followed on a scale of 0.0050 mol. In addition, gas released (presumably oxygen) during the reaction was measured with a manometer (the reaction vessel was attached to the reservoir of a semimicro hydrogenation apparatus for this measurement). A total of 58.0 mL of gas (theory is 0.0025 mol or 56.0 mL) was collected. The reaction products were chromatographed over a column of silica gel (100 g) packed as a slurry in hexane. The column was eluted with hexane (2 L), 10% methylene chloride in hexane (1.3 L), and finally with methylene chloride (2.3 L). Fractions of 100-mL volume were collected. Fraction 2 contained 0.140 g of a 1:3 mixture (measured by GLC) of 1-octadecene [0.035 g, 3%, mass spectrum *m/e* 252 ( $\text{M}^+$ ), 153 ( $\text{M}^+ - 99$ ), 139 ( $\text{M}^+ - 113$ ), 125 ( $\text{M}^+ - 127$ ), 111 ( $\text{M}^+ - 141$ ), 97 ( $\text{M}^+ - 155$ ), 83 ( $\text{M}^+ - 169$ ), 71 ( $\text{M}^+ - 181$ ), 69 ( $\text{M}^+ - 183$ )] and starting 1-bromooctadecane. Fraction 3 contained an additional 0.100 g of 1-bromooctadecane (total 0.205 g). Fractions 22–27 contained 0.646 g (0.001 20 mol, 54%) of crystalline material, mp 50–53 °C. Recrystallization from acetone gave 0.580 g of **di-*n*-octadecyl peroxide** as colorless crystals: mp 53–55 °C; mass spectrum *m/e* 523 ( $\text{M}^+ - 15$ ), 269 ( $\text{CH}_3(\text{CH}_2)_{17}\text{O}^+$ ).

Anal. Calcd for  $\text{C}_{36}\text{H}_{74}\text{O}_2$ : C, 80.22; H, 13.84. Found: C, 79.76; H, 14.11.

Fraction 28 contained 0.047 g (0.090 mmol, 4%) of crystalline material. Recrystallization from acetone gave colorless crystals of di-*n*-octadecyl ether, mp 58–60 °C (lit.<sup>31</sup> mp 57.8–58.4, 59–60, 62–63 °C).

Fractions 44–53 contained 0.200 g (0.000 74 mol 16%) of 1-octadecanol, infrared spectrum identical with that of an authentic sample.

**(*R*)-(-)-2-Bromooctane.** The procedure of Hudson<sup>20</sup> was followed using (*S*)-(+)-2-octanol [Aldrich Chemical Co., 20.0 g, 0.154 mol,  $\alpha_D^{25} + 7.69$  (neat),  $[\alpha]_D^{25} + 8.6^\circ$  (*c* 0.8730,  $\text{CHCl}_3$ )]. The crude product was distilled, giving 8.87 g of (*R*)-(-)-2-bromooctane: bp 64 °C (8.6 mm);  $\alpha_D^{25} - 42.53^\circ$  (neat); NMR ( $\text{CDCl}_3$ )  $\delta$  4.06 (sextuplet, 1 H, *J* = 6.5 Hz,  $>\text{CHBr}$ ), 1.64 (d, 3 H, *J* = 6.5 Hz,  $>\text{CHCH}_3$ ), 0.88 (t, 3 H, *J* = 5 Hz,  $-\text{CH}_3$ ).

**Reaction of (*R*)-(-)-2-Bromooctane with Potassium Superoxide. (*S,S*)-(+)-Di-2-octyl Peroxide.** Procedure A above was followed, using potassium superoxide (0.0107 mol), (*R*)-(-)-2-bromooctane (0.010 mol), benzene (15 mL), and dicyclohexyl-18-crown-6 (0.010 mol). The reaction was followed by VPC, using the previously described conditions. After 5 h, the reaction mixture contained 37% of olefins and 10% starting bromide. TLC (benzene) indicated the presence of two peroxidic products. The reaction mixture was worked up and there was obtained, following chromatography, di-2-octyl peroxide (0.637 g, 0.002 47 mol, 49%, 55% if based on unreacted starting material): bp 75–76 °C (0.1 mm);  $[\alpha]_D^{25} + 39.9^\circ$  (*c* 1.0384,  $\text{CHCl}_3$ ); NMR ( $\text{CDCl}_3$ )  $\delta$  4.04 (m, 2 H,  $>\text{CHOO}-$ ), 1.28 (m, 20 H,  $-\text{CH}_2-$ ), 1.17 (d, 6 H, *J* = 6 Hz,  $-\text{CHCH}_3$ ), 0.88 (t, 6 H, *J* = 5 Hz,  $-\text{CH}_2\text{CH}_3$ ).

Anal. Calcd for  $\text{C}_{16}\text{H}_{34}\text{O}_2$ : C, 74.36; H, 13.26. Found: C, 73.86; H, 13.65.

Also obtained from the chromatography was a second peroxidic product, assumed to be 2-octyl hydroperoxide (0.125 g, 0.000 857 mol, 8%): NMR ( $\text{CDCl}_3$ )  $\delta$  8.32 (s, 1 H, OH), 4.07 (m, 1 H,  $>\text{CHOO}-$ ), 1.28 (m, 10 H,  $-\text{CH}_2-$ ), 1.20 (d, 3 H, *J* = 6 Hz,  $-\text{CHCH}_3$ ), 0.88 (t, 3 H, *J* = 5 Hz,  $-\text{CH}_2\text{CH}_3$ ).

**Reduction of (*S,S*)-(+)-Di-2-octyl Peroxide with Lithium Aluminum Hydride.** A solution of (*S,S*)-(+)-di-2-octyl peroxide (0.233 g, 0.903 mmol) in ether was added to a mixture of  $\text{LiAlH}_4$  (0.076 g, 2.0 mmol) and ether (total ether volume 35 mL). The mixture was stirred at room temperature. TLC after 2.5 h indicated partial reduction. No further change was noted up to 24 h. Additional  $\text{LiAlH}_4$  (0.076 g) was added. Further reduction occurred. A trace of starting material remained 6 h after the additional  $\text{LiAlH}_4$  was added, but the reaction mixture was worked up by cautious addition of water. A white precipitate formed. Additional water was added and the ether layer was separated. The aqueous layer was extracted with ether (3  $\times$  50 mL) and the combined ether extracts were dried ( $\text{MgSO}_4$ ). The drying agent and solvent were removed leaving 0.18 g of a clear oil. The oil was chromatographed on silica gel (12 g) packed as a slurry in 7.5% ethyl acetate-benzene. Elution was with the same solvent system and 5-mL fractions were collected. Starting peroxide was detected in fractions 4–7. Fractions 10–25 contained the alcohol and were pooled, giving 0.113 g of (*S*)-(+)-2-octanol:  $[\alpha]_D^{25} + 7.7^\circ$  (*c* 0.9884,  $\text{CHCl}_3$ ); NMR identical with that of an authentic sample of 2-octanol. The sample was checked by VPC before measuring the specific rotation and was found to be >98% pure.

**Reaction of 2-Octyl Tosylate with Potassium Superoxide.** Procedure A above was followed, using  $\text{KO}_2$  (0.005 45 mol), benzene (10 mL), 2-octyl tosylate [1.427 g, 0.0050 mol, prepared from (*R*)-(-)-2-octanol of  $\alpha_D^{25} - 7.40^\circ$  (neat),  $[\alpha]_D^{25} - 8.3^\circ$ ], and dicyclohexyl-18-crown-6 (0.050 mol). TLC (benzene and 10% ethyl acetate-benzene) after 4 h indicated a trace of starting material remaining. Additional  $\text{KO}_2$  (0.0018 mol) was added and stirring was continued for 3 h. The reaction mixture was worked up and stored overnight in methylene chloride over  $\text{MgSO}_4$ . TLC indicated no starting material and two main nonvolatile products. VPC of a sample of the reaction mixture after 4 h indicated formation of octenes in 16% yield. Chromatography (7.5% ethyl acetate-benzene) separated the two nonvolatile products. Eluted first was 2-octadecyl peroxide (0.340 g, 0.001 31 mol, 52%); NMR spectrum in  $\text{CDCl}_3$  was identical with that of 2-octadecyl peroxide prepared from 2-bromooctane.

The second product eluted was (*S*)-(+)-2-octanol (0.089 g, 0.000 685 mol, 13%): NMR spectrum was identical with that of authentic 2-octanol; purity by VPC >99%;  $[\alpha]_D^{25} + 7.4^\circ$  (*c* 0.9135,  $\text{CHCl}_3$ ).

**Reaction of 2-Octyl Mesylate with Potassium Superoxide.** Procedure A above was followed, using  $\text{KO}_2$  (0.006 82 mol), benzene (15 mL), 2-octyl mesylate (0.0050 mol, prepared from (*S*)-(+)-2-octanol,  $[\alpha]_D^{25} + 8.6^\circ$ ), and dicyclohexyl-18-crown-6 (0.0050 mol). The reaction mixture was worked up after 4 h. TLC indicated some remaining starting material and two main products. VPC showed the presence of octenes in a yield of 14%. Chromatography (7.5% ethyl

acetate-benzene) separated the nonvolatile materials. There was obtained di-2-octyl peroxide (0.285 g, 0.0011 mol, 4), NMR spectrum in  $\text{CDCl}_3$  identical with that of di-2-octyl peroxide prepared from 2-bromooctane.

Eluted last was (*R*)-(-)-2-octanol (0.125 g, 0.00096 mol, 19%): NMR spectrum in  $\text{CDCl}_3$  identical with that of authentic 2-octanol; purity by VPC >99%;  $[\alpha]_D^{25} -7.5^\circ$  (*c* 0.8648,  $\text{CHCl}_3$ ).

(*S*)-(+)-2-Bromooctane. The procedure of Hudson<sup>20</sup> was used. In this way (*R*)-(-)-2-octanol  $[\alpha]_D^{25} -8.2^\circ$  (*c* 1.166,  $\text{CHCl}_3$ ), 30.0 g, 0.231 mol] was converted into (*S*)-(+)-2-bromooctane (11.98 g, bp  $59.5^\circ\text{C}$  (6.0 mm),  $\alpha_{\text{obsd}} +39.33^\circ$ ).

(*R*)-(-)-2-Hydroperoxyoctane. A mixture of crushed potassium superoxide (5.32 g, 0.075 mol) and DMF (100 mL) containing dicyclohexyl-18-crown-6 (9.35 g, 0.025 mol) was stirred at room temperature for 1 h and then was cooled in an ice bath. A solution of (*S*)-(+)-2-bromooctane ( $\alpha_{\text{obsd}} +39.33^\circ$ , 4.83 g, 0.025 mol) in DMF (20 mL) was added dropwise (15 min) to the rapidly stirred  $\text{KO}_2$ -DMF mixture. The resulting mixture was allowed to stir for an additional 15 min at ice-bath temperature. The reaction mixture was then worked up by pouring into ice-water (500 mL) and extracting with ether ( $3 \times 100$  mL). The ether extract was dried over  $\text{MgSO}_4$ . Thin layer chromatography at this point revealed two peroxidic products. The extract was filtered, concentrated, and chromatographed on a silica gel column (300 g) that had been packed as a slurry in benzene. The column was eluted with benzene (1 L) and 5% ethyl acetate-benzene (3 L). Fractions of 110-mL volume were collected. Fractions 5-7 contained di-2-octyl peroxide (0.643 g, 0.00252 mol, 20%), having an NMR spectrum identical with that of a previously described sample. Fractions 15-22 contained (*R*)-(-)-2-hydroperoxyoctane (1.17 g, 0.0081 mol, 32%); bp  $40-41^\circ\text{C}$  (0.10 mm) (lit.<sup>32</sup> bp  $58-59^\circ\text{C}$  (0.4 mm));  $[\alpha]_D^{25} -2.5^\circ$  (*c* 1.050,  $\text{CHCl}_3$ ); NMR ( $\text{CDCl}_3$ )  $\delta$  4.08 (six-line signal, 1 H,  $J = 6$  Hz,  $-\text{CHOO}-$ ), 1.33 (m), 1.21 (d, 3 H,  $J = 7$  Hz,  $-\text{CH}_3$ ), 0.88 (t, 3 H,  $J = 5$  Hz,  $-\text{CH}_3$ ).

Reduction of (*R*)-(-)-2-Hydroperoxyoctane with Lithium Aluminum Hydride. A solution of (*R*)-(-)-2-hydroperoxyoctane ( $[\alpha]_D^{25} -2.5^\circ$ , 0.292 g, 0.0020 mol) in ether (2 mL) was added to a stirred mixture of  $\text{LiAlH}_4$  (0.095 g) and ether (35 mL). Two additional portions of  $\text{LiAlH}_4$  (0.1 g each) were added at intervals when TLC indicated that the reaction was incomplete. After the mixture was stirred overnight, the starting material was completely gone. Water was added carefully to the reaction mixture and stirring was continued until only a white precipitate remained in the ether. The ether was decanted and the residue was washed with more ether. The combined ether solutions were dried ( $\text{MgSO}_4$ ), filtered, and concentrated (0.261 g, 0.0020 mol). NMR indicated that the product was essentially pure (*R*)-(-)-2-octanol,  $[\alpha]_D^{25} -7.6^\circ$  (*c* 0.7495,  $\text{CHCl}_3$ ).

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