Reactivity of Superoxide Ion with Carbonyl Compounds in Aprotic Solvents

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Abstract: Benzaldehyde and ketones undergo no net elementary reaction with superoxide ion ($O_2^-\cdot$) in inert solvents such as pyridine, toluene, and benzene. Esters, however, are hydrolyzed via an initial reversible nucleophilic addition of $O_2^-\cdot$ to the carbonyl carbon followed by loss of alkoxide from the tetrahedral intermediate (rather than its reduction). This pathway is strongly supported by the relative second-order rate constants for the reaction of $O_2^-\cdot$ in pyridine with ethyl acetate (1) and phenyl acetate (10^4) together with results earlier reported in the literature. For the ketones and benzaldehyde, reversible initial addition of $O_2^-\cdot$ to the carbonyl must occur as well, but the absence of a viable leaving group precludes a net reaction. The decomposition products of $O_2^-\cdot$ *are* highly reactive with benzaldehyde, apparently through a base-catalyzed process. These alkaline decomposition products also are reactive toward acetonitrile. The products and mechanisms for the reactions of $O_2^-\cdot$ and its decomposition products in these systems are discussed.

Introduction

The reactivity of superoxide ion, $O_2^-\cdot$, with organic molecules has been the subject of considerable recent interest for two reasons. The discovery and subsequent elaboration of the fact that superoxide is generated ubiquitously in aerobic organisms made it biochemically important to understand the chemical reactivity of $O_2^-\cdot$. Furthermore, because a "new" species is in hand, this simple ion represents an opportunity to examine and broaden our understanding of elementary reactivity patterns from a purely fundamental chemical view.

Stimulants to such studies have been the development of electrochemical methods[1-6] to generate pure, stable solutions of $O_2^-\cdot$ and the somewhat later development of the crown-ether solubilization of KO_2 in organic solvents,[7-10] again to give relatively stable solutions of $O_2^-\cdot$.[11]

Both methods of $O_2^-\cdot$ generation (electrochemical and crown ether/KO_2) have been used here to study the reactivity of $O_2^-\cdot$ toward organic compounds; in particular a functional group survey approach has been adopted. As reported recently,[12] we have found that while compounds with certain organic functional groups react to give observable products, examination of the $O_2^-\cdot$ decay (electrochemically) reveals the absence of an increased rate of $O_2^-\cdot$ loss, above the usual slow autodisproportionation, for these substrates. Close examination of several of the systems has led us to conclude that much of the chemistry that has been obsermed is due not to reections of $O_2^-\cdot$ with the organics, but to reactions of the decomposition products of $O_2^-\cdot$ after its disproportionation. We report here on the reactivities of simple aldehydes, ketones, and esters in pyridine, toluene, and benzene (inert solvents). Some interesting chemistry of the KO_2-crown ether system with benzaldehyde in acetonitrile is also revealed. Acetonitrile is apparently inert to superoxide itself, but is highly reactive to the basic decomposition products of $O_2^-\cdot$.

Several previous workers have included aromatic aldehydes in their studies, and concluded that $O_2^-\cdot$ oxidizes benzaldehyde to either benzoic acid or perbenzoic acid.[11,13-17] In inert solvents this is indeed what we observe after long reaction times, but the chemistry along the way is complex and interesting. Aliphatic aldehydes give complicated product mixtures. Esters,[11,14] as previously assumed, *do* undergo elementary reactions with superoxide. On the basis of product and kinetic data (along with appropriate controls), a reasonable picture of the elementary chemistry of $O_2^-\cdot$ with the carbonyl functionality can be presented.

Experimental Section

Materials. Solvents other than acetonitrile and pyridine were reagent grade and dried over molecular sieve. Acetonitrile and pyridine were Burdick and Jackson high-purity solvents (H_2O, 0.009%) which were used as received. (Further purification attempts with these materials resulted in no improvement in purity. Gas chromatographic and electrochemical analysis confirmed the extremely low water contents specified by the supplier.)

KO_2 was from Alfa Inorganics (96.5%), and all other inorganics were Mallinckrodt AR grade. Benzyl alcohol was Baker AR, distilled. Benzaldehyde was Aldrich reagent, and was distilled immediately before each use through a 3-ft glass helices packed column under vacuum with an argon bleed. The material was kept rigorously anaerobic at all times. 18-Crown-6 ether was synthesized according to a literature procedure,[18] dried, and stored in a vacuum desiccator. All other organics were from Aldrich, reagent grade, except for *m*-chloroperbenzoic acid, which was technical grade (85%).

Methods. KO_2 Experiments. In a typical experiment, KO_2 (finely ground in a dry N_2 atmosphere glovebag) and crown ether were weighed in the glovebag. These materials were added to a round-bottom flask (already containing solvent and a stirring bar) fitted with a serum cap, an inlet N_2 bubbler, and a $CaCl_2$ drying tube with serum cap and exit needle. The vessel for small-scale runs was a small vial with a fresh serum cap fitted with Ar inlet and outlet needles. The organic substrate (benzaldehyde or other reagent) was then injected into the vessel. During the additions and the reaction the solution was continuously bubbled with nitrogen and magnetically stirred as rapidly as feasible. In some runs, the organic reagent was added before the KO_2 and a sample removed for analysis prior to initiation of the reaction.

In most runs, the reaction mixture was analyzed several times during the reaction. Small samples were withdrawn through the serum cap and either injected directly into the gas chromatograph, or neutralized and then analyzed. Finally, the total mixture was added to aqueous acid and the products were isolated by extraction and recrystallization.

Runs with salts other than KO_2 were handled identically. The gas chromatography involved a dual column analysis on Carbowax 20M at 135 °C for reactions in pyridine. Acetonitrile reactions were analyzed on SE-30. Mass spectra, NMR, IR, and melting point determinations as well as comparison of GC retention times to those of known compounds were used to identify products indicated.

$C_6H_5COCH_2CN$ (mp 78-80 °C, lit. 81-82 °C)[19] had IR (cm^{-1}) 1700 (C=O), 2270 (C≡N), and 3000 (Ar-H); NMR δ 7.3-8.1 (m, ArH) and 4.14 (s, CH_2); mass spectrum *m/e* 145 (P), 105 (C_6H_5CO), 77 (C_6H_5), and 40 (CH_2CN), in agreement with the assigned structure.

Electrochemical Measurements. Superoxide ion was generated by electrochemical reduction of O_2 at a gold electrode (−1.2 V vs. SCE)

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Table I. Reaction of Superoxide Ion with Esters in Pyridine[a]

initial [ester], mM	initial $[O_2^-\cdot]$, mM	initial $O_2^-\cdot$ decay rate, $\mu M\ s^{-1}$	k_2, $M^{-1}\ s^{-1}$
	A. Ethyl Acetate		
51	4.70	3.00	0.012
51	0.34	0.16	0.009
51	1.10	0.63	0.011
16	1.10	0.21	0.012
31	1.20	0.39	0.010
104	1.10	0.73	0.007
26	1.50	0.74	0.018
50	1.30	0.84	0.013
			av 0.011 ± 0.002
	B. Phenyl Acetate[b]		
0.10	0.044	0.72	160 ± 50

[a] $O_2^-\cdot$ generated by controlled-potential electrolysis of O_2 prior to the addition of substrate. Concentrations of $O_2^-\cdot$ monitored by cyclic voltammetry (see Experimental Section and Results). [b] Difficult to measure because of its rapid rate of reaction. As measured by direct cyclic voltammetric reduction of O_2 in the presence of substrate (Figure 2), k_2 has a value of 140 ± 70 $M^{-1}\ s^{-1}$ (see Results).

in pyridine with 0.1 M tetra-*n*-propylammonium perchlorate. Superoxide solutions (0.8–6.0 mM) were degassed with argon to remove dissolved O_2 prior to addition of substrate. The concentration of $O_2^-\cdot$ was monitored by linear sweep voltammetry with the anodic peak current measured at −0.7 V. Standardization of the current in relation to $O_2^-\cdot$ concentration was accomplished by coulometric analysis.

The electrochemical instrumentation consisted of a Princeton Applied Research Corp. Model 173A potentiostat, Model 179 digital coulometer, Model 175 Universal Programmer, and a Hewlett-Packard Model 7030A X-Y recorder. The three-electrode system included an Ag/AgCl (aqueous Me_4NCl) cracked bead reference electrode adjusted to 0.000 V vs. SCE, a Pt flag auxiliary electrode separated from the bulk of the solution by a medium porosity fritted disk, and a gold working electrode. The reference electrode was held in a Liggin capillary to minimize *iR* errors in the measured potential. For cyclic voltammetry experiments a Beckman Pt disk electrode (0.23 cm^2 area) was used as the working electrode. The electrolysis cell consisted of either a Leeds and Northrup polyethylene cell top with a 100-mL electrolysis beaker or a Brinkmann titration cell. Solutions were degassed with high-purity argon for 10 min prior to analysis and blanketed during analysis to exclude oxygen.

Results

Electrochemical Monitoring of $O_2^-\cdot$ Reactivity. Electroreduction of oxygen dissolved in pyridine yields stable, well-behaved solutions of superoxide ion. In our hands this solvent yielded better stability and reproducibility for $O_2^-\cdot$ and its reaction products than did acetonitrile or dimethyl sulfoxide. In the millimolar range, the half-life of $O_2^-\cdot$ in pyridine is 4–12 h for the concentrations that have been used. Typically, in the absence of added substrate, $-d[O_2^-\cdot]/dt = 0.04\ \mu M\ s^{-1}$ for 1.0 mM $O_2^-\cdot$. The rates of reaction for various substrates with $O_2^-\cdot$ have been measured in the presence of excess substrate by monitoring the concentration of $O_2^-\cdot$ as a function of time with linear sweep voltammetry. All rates of reactions that are reported here have been corrected for the slow background decomposition of $O_2^-\cdot$ (using 0.04 $\mu M\ s^{-1}$).

Benzaldehyde. Addition of impure benzaldehyde (reagent grade, as supplied) causes rapid decomposition of $O_2^-\cdot$. However, when this aromatic aldehyde is carefully purified by slow vacuum distillation under argon immediately prior to its addition to freshly prepared $O_2^-\cdot$ solutions in pyridine (also under argon), the rate of decomposition of $O_2^-\cdot$ does not increase beyond that in the absence of substrate. Some measured rates (at given concentrations of pure C_6H_5CHO) for 1.2 mM $O_2^-\cdot$ are 0.12 (1.0 mM), 0.06 (2.0 mM), 0.06 (20 mM), 0.05 $\mu M\ s^{-1}$ (42.5 mM). We have performed dozens of these experiments with many different samples of benzaldehyde, and the data given here are entirely typical. Storage of purified benzaldehyde in a flask under argon for even 1 day often resulted in increased rates with $O_2^-\cdot$ (e.g., 0.12 $\mu M\ s^{-1}$ for quite pure material, >1 $\mu M\ s^{-1}$ for crudely distilled or "reagent grade" material). When freshly purified benzaldehyde is added to partially decomposed $O_2^-\cdot$ solutions, an increase in the rate of $O_2^-\cdot$ disappearance also is observed.

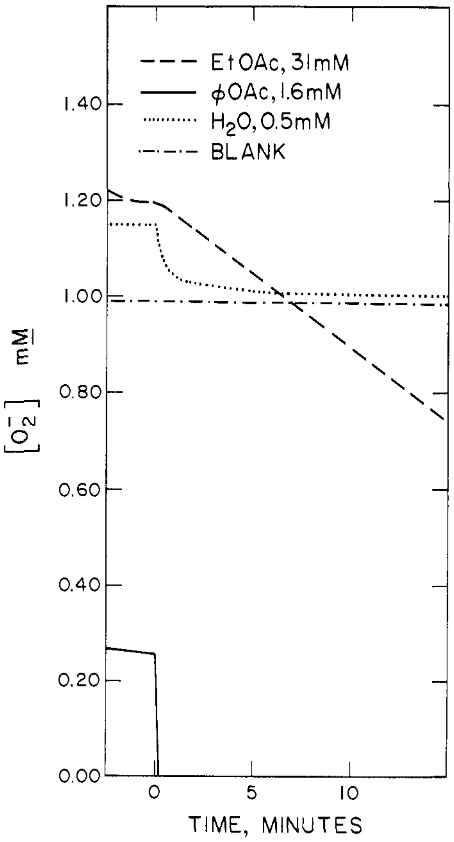


Figure 1. Rate of disappearance of $O_2^-\cdot$ in the presence of various substrates in pyridine (0.1 M tetra-*n*-propylammonium perchlorate).

A survey by cyclic voltammetric generation of $O_2^-\cdot$ indicates no loss of $O_2^-\cdot$ in the presence of the ketones benzophenone, cyclohexanone, acetone, or 2-butanone (all 0.1 M).

Esters. Addition of ethyl acetate or phenyl acetate to $O_2^-\cdot$ solutions results in reactions that are first order in $O_2^-\cdot$ and first order in ester (typical runs in Figure 1, data summarized in Table I). For ethyl acetate and $O_2^-\cdot$, $k_2 = 1.1\ (\pm 0.2) \times 10^{-2}\ M^{-1}\ s^{-1}$, and for phenyl acetate and $O_2^-\cdot$, $k_2 = 1.6\ (\pm 0.5) \times 10^2\ M^{-1}\ s^{-1}$. In each case, the reactions have been measured in the presence of excess ester to minimize the possibility of secondary processes and more complicated kinetics.

In some cases, the rate of reaction with $O_2^-\cdot$ also has been determined by the cyclic voltammetric reduction of O_2 to $O_2^-\cdot$ in the presence of substrate. As illustrated by Figure 2, the peak current for the reoxidation of $O_2^-\cdot$ decreases in the presence of phenyl acetate and provides a measure of the extent of the reaction. Comparison of the cathodic and anodic peak currents provides a measure of the pseudo-first-order rate constant.[20] By use of various concentrations of O_2 and phenyl acetate such measurements establish that the reaction is first order in $O_2^-\cdot$ and first order in phenyl acetate. Division of the pseudo-first-order rate constant by the concentration of phenyl acetate gives k_2, the second-order rate constant. The value of k_2 for $CH_3CO_2C_6H_5$ is 140 ± 70 $M^{-1}\ s^{-1}$; for $C_6H_5CO_2C_6H_5$ (also measured in this manner) the value of k_2 is 5 ± 3 $M^{-1}\ s^{-1}$.

Reaction of Aldehydes by Chemical Studies. The alternative method for the study of the reactivity of $O_2^-\cdot$ has been by use of KO_2 that has been solubilized by 18-crown-6 ether (CE);

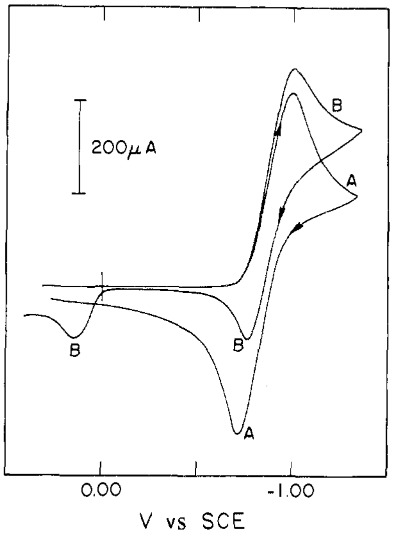


Figure 2. Cyclic voltammograms for (A) O_2 at 1 atm (4.2 mM) and (B) O_2 at 1 atm in the presence of 7.9 mM phenyl acetate in a pyridine (0.1 M tetra-*n*-propylammonium perchlorate) solvent system at a platinum electrode (area 0.23 cm^2). Scan rate, 0.1 V s^{-1}

such an approach is necessary for efficient product studies because the concentrations of $O_2^{-}\cdot$ from electrochemical generation are too small ($<10^{-2}$ M). Examination of a range of solvents indicates that both dimethyl sulfoxide and acetonitrile become involved in the reaction. While the former solvent gave rather intractable products, the acetonitrile reaction products were identified and semiquantitated. The chemistry is rather interesting, and is discussed below.

Acetaldehyde in dimethyl sulfoxide reacts to yield a tar, but no observable volatile product. Presumably, an aldol-type oligomerization or polymerization occurs, perhaps with incursion of solvent.

Benzaldehyde in Pyridine. Because benzaldehyde cannot give aldol-type chemistry our studies have centered on this molecule.

Early investigations by gas chromatography revealed that benzyl alcohol is the only observable volatile product of the $KO_2/CE/C_6H_5CHO$ system in pyridine. With the ratio of these reactants at 2.0/0.1/1.0, respectively (0.07 M in CE), the initial rate of benzyl alcohol formation has been found to be close to one-half the initial rate of benzaldehyde disappearance. Workup of the reaction mixture yields benzoic acid in varying, but always major, amounts. If allowed to stir for 2 days, the reaction mixture (excess KO_2) gives a 95% yield of purified benzoic acid. This brought to mind the Cannizzaro reaction, which indeed does occur at a rapid rate ($t_{1/2} \approx 0.3$ h) in pyridine with $KOH/CE/C_6H_5CHO$ (2/0.1/1.0; CE was 0.07 M) to give the expected products. Neither K_2CO_3 nor H_2O_2 reacts with benzaldehyde under the reaction conditions. The reaction of *m*-chloroperbenzoic acid with benzaldehyde in the presence of K_2CO_3 and CE proceeds rapidly (as monitored by aldehyde loss), presumably to give benzoic acid.[21]

$$2C_6H_5CHO + OH^- \rightarrow C_6H_5CO_2^- + C_6H_5CH_2OH$$

Benzyl alcohol reacts with KO_2/CE at about ⅓ the rate that does benzaldehyde. The product of this reaction is benzaldehyde. When KO_2/CE is allowed to stand in pyridine for 3 h followed by addition of benzyl alcohol, the alcohol is oxidized at a fivefold higher initial rate than when it is added at the same time as all the other reagents.

Because the acidic (or neutral) workup almost certainly leads to further reactions of the aldehyde (from H_2O_2 or other species generated from unreacted $O_2^{-}\cdot$), the product analysis also was performed for the reaction with excess C_6H_5CHO ($KO_2/CE/C_6H_5CHO$ = 1/1/3) in pyridine. In two runs the isolated products in toto accounted for 89 and 82%, respectively, of the original aldehyde. Relative to the reacted aldehyde, gas chromatographic analysis indicated yields of 17 and 5% $C_6H_5CH_2OH$, respectively; the isolated yields of benzoic acid were 31 and 44%, respectively. There were no traces of any other product, and in control runs for the extraction and recrystallization of benzoic acid we achieved variable 65–85% recoveries (at best) for these small-scale complex mixtures (pyridine, acidic water, crown ether, benzene extractions). On the basis of our longer time runs with excess KO_2, we conclude that benzoic acid is the ultimate end product of the reaction, but that benzyl alcohol is formed and slowly reacts further as described above.

Benzaldehyde in Acetonitrile. Much of the preliminary work involved acetonitrile as the solvent. After a considerable amount of experimentation, the major products of the reaction of KO_2/CE with benzaldehyde in acetonitrile have been found to be cinnamonitrile ($C_6H_5CH{=}CHCN$, cis and trans) and benzoylacetonitrile ($C_6H_5COCH_2CN$) along with benzoic acid and small amounts of benzyl alcohol. The relative yields of these products depend upon the C_6H_5CHO/KO_2 ratio and, perhaps, on some as yet undetermined variables. As in pyridine as solvent, benzaldehyde does not undergo an elementary reaction with $O_2^{-}\cdot$, but it does with $O_2^{-}\cdot$ decomposition products and with acetonitrile anion (see Discussion section).

Examples of yields based upon initial C_6H_5CHO are 5% *cis*-cinnamonitrile, 60% *trans*-cinnamonitrile, and 30% benzoylacetonitrile in a run with high KO_2 ($C_6H_5CHO/CE/KO_2$ equal to 1/0.1/2); 16% unreacted C_6H_5CHO, 3% *trans*-cinnamonitrile, 35% benzoylacetonitrile, and 25% benzoic acid in a run with excess aldehyde ($C_6H_5CHO/CE/KO_2$ equal to 3/1/1). When 0.13 g (2.4 mmol) of KOH is added to 0.12 mL (1.2 mmol) of C_6H_5CHO and 0.032 g (0.12 mmol) of CE in 2 mL of CH_3CN, a 76% yield (based upon starting C_6H_5CHO) of *cis*- and *trans*-cinnamonitrile is obtained within 1 min.

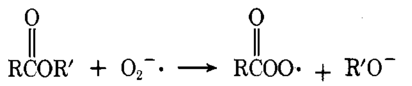
Cinnamonitrile is stable under the reaction conditions [0.032 g (0.12 mmol) of CE, 0.17 g (2.4 mmol) of KO_2 in 2 mL of pyridine] but benzoylacetonitrile is not. From another control experiment, cinnamonitrile appears to be unstable in CE/CH_3CN in the presence of basic H_2O_2(aq).

Discussion

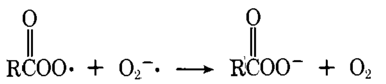
Esters. The present results confirm that esters undergo a primary reaction with $O_2^{-}\cdot$, while aromatic aldehydes and typical ketones do not. That esters are hydrolyzed to carboxylic acids and alcohols by $O_2^{-}\cdot$ has been reported previously;[14,16] the data of Table I provide convincing evidence that this is an elementary reaction. The pathway presented in eq 1–6 is a slightly modified version of that proposed by Magno and Bontempelli[16] for their study of electrochemically generated $O_2^{-}\cdot$ in the presence of esters. Various other possibilities for steps subsequent to eq 2 were considered by those authors, but the electrochemical stoichiometry and the observation of an easily reduced transient (diacyl peroxide) led them to favor eq 3–5. San Fillipo and co-workers[14] have shown that acyl-oxygen scission occurs and that the approximate order of reactivity for different *n*-octanoate esters follows typical ester acyl-oxygen cases. They also obtained evidence that reaction of diacyl peroxide with KO_2 leads to carboxylic acid (reaction 6).[22]

The second-order rate constants for the reaction of $O_2^{-}\cdot$ in pyridine with the two acetate esters in the present study are 1.1×10^{-2} ($CH_3CO_2C_2H_5$) and 1.6×10^{2} M^{-1} s^{-1} ($CH_3CO_2C_6H_5$). This 10^4 ratio of rates at first seems surprising, but upon closer examination it is, in fact, consistent with other data for ethyl vs. phenyl esters in reactions with effective nucleophiles, as will be addressed now.[23,24]

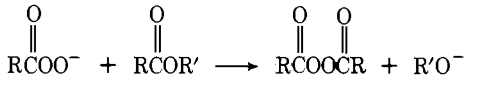
$$\mathrm{O_2 + e^- \longrightarrow O_2^{-}\cdot} \qquad (1)$$


(2)

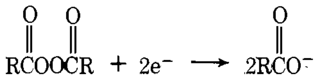
$$\mathrm{R\overset{O}{\overset{\|}{C}}OR' + O_2^{-}\cdot \longrightarrow R\overset{O}{\overset{\|}{C}}OO\cdot + R'O^-} \qquad (2)$$


(3)

$$\mathrm{R\overset{O}{\overset{\|}{C}}OO\cdot + O_2^{-}\cdot \longrightarrow R\overset{O}{\overset{\|}{C}}OO^- + O_2} \qquad (3)$$

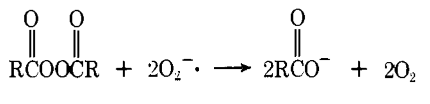

(4)

$$\mathrm{R\overset{O}{\overset{\|}{C}}OO^- + R\overset{O}{\overset{\|}{C}}OR' \longrightarrow R\overset{O}{\overset{\|}{C}}OO\overset{O}{\overset{\|}{C}}R + R'O^-} \qquad (4)$$


(5)

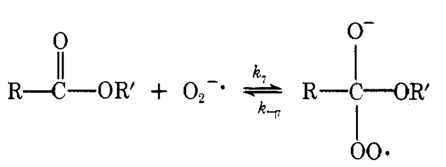
$$\mathrm{R\overset{O}{\overset{\|}{C}}OO\overset{O}{\overset{\|}{C}}R + 2e^- \longrightarrow 2R\overset{O}{\overset{\|}{C}}O^-} \qquad (5)$$

or

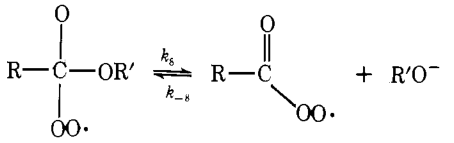

(6)

$$\mathrm{R\overset{O}{\overset{\|}{C}}OO\overset{O}{\overset{\|}{C}}R + 2O_2^{-}\cdot \longrightarrow 2R\overset{O}{\overset{\|}{C}}O^- + 2O_2} \qquad (6)$$

If eq 2 occurs via the usual nucleophilic attack at carbonyl, it can be expanded in eq 7 and 8, both being reversible. This


(7)

$$\mathrm{R{-}\overset{O}{\overset{\|}{C}}{-}OR' + O_2^{-}\cdot \underset{k_{-7}}{\overset{k_7}{\rightleftharpoons}} R{-}\underset{OO\cdot}{\underset{|}{\overset{O^-}{\overset{|}{C}}}}{-}OR'} \qquad (7)$$


(8)

$$\mathrm{R{-}\underset{OO\cdot}{\underset{|}{\overset{O}{\overset{|}{C}}}}{-}OR' \underset{k_{-8}}{\overset{k_8}{\rightleftharpoons}} R{-}\overset{O}{\overset{\|}{C}}{-}OO\cdot + R'O^-} \qquad (8)$$

followed by reaction 3

is a situation in which k_8 will be highly dependent upon the acidity of R'OH (i.e., the stability of $\mathrm{R'O^-}$), and the rate-limiting step will depend upon the competition between k_{-7} and k_8. For poor leaving groups k_8 will be slow and rate limiting, but for good leaving groups k_8 will be much more rapid, causing it to be competitive with k_{-7}.

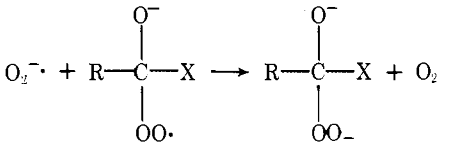
In the present case, there are tetrahedral intermediates in which R' is C_6H_5 or C_2H_5. The situation here is much akin to that which obtains for the imidazole ($pK_a \sim 7$) catalyzed hydrolysis of acetates.[23-25] That process exhibits a similar 10^4 difference between phenyl and ethyl esters, ascribed to a change in the rate-limiting step with imidazole as the nucleophile. In our case, the loss of $C_6H_5O^-$ in eq 8 can compete much more effectively with the loss of $O_2^{-}\cdot$ (k_{-7}) than can the corresponding loss of $C_2H_5O^-$ from the ethyl ester.

In the Magno and Bontempelli work[16] the second-order rate constants for $O_2^{-}\cdot$ hydrolysis of phenyl benzoate and *p*-chlorophenyl benzoate in DMF are 3 (in good agreement with the value obtained here in pyridine) and 25 $M^{-1}\ s^{-1}$, respectively. The large (almost tenfold) increase observed upon the substitution of a *p*-chloro group in the phenolic moiety is again in accord with the mechanism of eq 7 and 8 (and is like that seen for imidazole attack on acetates, but not for attack by a strong base like OH^-).[23,24]

Aldehydes. The electrochemical data clearly indicate that $O_2^{-}\cdot$ does not undergo an elementary reaction with benzaldehyde. The rate of $O_2^{-}\cdot$ disappearance in pyridine is unaffected by relatively high concentrations of pure benzaldehyde for at least 1 half-life of the superoxide. Impure aldehyde, however, causes a rapid $O_2^{-}\cdot$ loss which is then followed by loss of aldehyde. In our view, this is due to proton-catalyzed $O_2^{-}\cdot$ decomposition as the result of a benzoic acid impurity. On the other hand, if benzaldehyde is added to a largely decomposed solution of superoxide ion in pyridine, then an accelerated decomposition of the remaining superoxide occurs. In accord with this result, when benzaldehyde is allowed to stand in the presence of $O_2^{-}\cdot$ for 0.5 h or more, the products of an apparent attack upon aldehyde are observed. Our conclusion is that the decomposition products of $O_2^{-}\cdot$ are highly reactive toward benzaldehyde, with almost no fundamental reactivity between the original reagents.

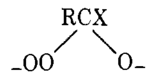
The subject of the aldehyde decomposition products will be addressed later, but first the lack of reactivity between $O_2^{-}\cdot$ and benzaldehyde needs to be considered. As discussed in the previous section, there is an elementary reaction of $O_2^{-}\cdot$ with esters; the carbonyl group of aldehydes and ketones should be at least as reactive toward the addition reaction. We believe that it is, but that the tetrahedral adduct does not undergo chemistry that is competitive with the reversal of the original addition (k_{-7}). That this is realistic is supported by the relative rates for the ethyl and phenyl esters (Table I), in which k_{-7} must be dominant for the poorer leaving ethoxide case. For aldehydes and ketones the absence of a viable leaving group precludes elimination as a productive mode, so that the original addition must entirely reverse.

An alternative to reactions 7, 8, and 3 (the hydrolysis pathway) is an electron transfer from superoxide ion to the peroxy radical generated in the addition step (i.e., eq 9 rather


(9)

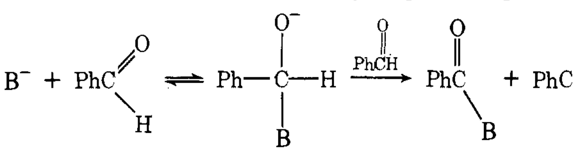
$$\mathrm{O_2^{-}\cdot + R{-}\underset{OO\cdot}{\underset{|}{\overset{O^-}{\overset{|}{C}}}}{-}X \longrightarrow R{-}\underset{OO^-}{\underset{|}{\overset{O^-}{\overset{|}{C}}}}{-}X + O_2} \qquad (9)$$

than eq 8 after eq 7), and then decomposition of the dianionic tetrahedral intermediate.[14] This bimolecular reaction of two anions would be expected to be slow and apparently cannot compete with the reversal of the addition or loss of X^- (k_{-7} and k_8), on the basis of the experimental results. If it did, not only would aldehydes and ketones react, but the reaction of ethyl and phenyl esters would be equally rapid in terms of the rate of $O_2^{-}\cdot$ disappearance. Although the reduced intermediate



would favor phenoxide loss over ethoxide loss, it could not revert to superoxide ion.[26]

Products of Benzaldehyde Reaction. The reaction of benzaldehyde with $O_2^{-}\cdot$ decomposition products, apparently to a major degree, is a Cannizzaro-type process that yields benzyl alcohol and an oxidized benzaldehyde species (eq 10).[27] For


(10)

$$\mathrm{B^- + PhC{\overset{O}{\underset{H}{\lessgtr}}} \rightleftharpoons Ph{-}\underset{B}{\underset{|}{\overset{O^-}{\overset{|}{C}}}}{-}H \xrightarrow{Ph\overset{O}{\overset{\|}{C}}H} Ph\overset{O}{\overset{\|}{C}}{-}B + PhCH_2O^-} \qquad (10)$$

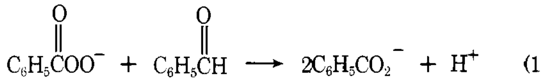
the reaction conditions, KOH gives a rapid and efficient Cannizzaro reaction. The benzyl alcoholate that is formed in the presence of KO_2 is slowly reoxidized to benzaldehyde, so that it is seen as an intermediate rather than a product. This is confirmed by our experiments with benzyl alcohol as the substrate.

The nature of B^- is not clear. One possibility is the HO_2^- species, which can be formed rapidly via eq 11, in which the H^+ to form $HO_2\cdot$ is derived from the solvent, the electrolyte

$$\mathrm{O_2^{-}\cdot + HO_2\cdot \rightarrow O_2 + HO_2^-} \qquad (11)$$

in the electrochemical studies, or trace impurities. The rate constant for this reaction in water is close to $10^8\ M^{-1}\ s^{-1}$ and should be similar in pyridine; small amounts of $HO_2\cdot$ would be sufficient to give the slow rates that are observed for $O_2^-\cdot$ disappearance (the disproportionation of $2O_2^-\cdot$ species without acid catalysis is at most extremely slow, $<0.3\ M^{-1}\ s^{-1}$).[28,29]

If HO_2^- were B^- in eq 10, then the products would be $C_6H_5CO_3^-$ and $C_6H_5CH_2OH$. The rapid reaction of *m*-$ClC_6H_4CO_3H$ (an available and similar peracid) with benzaldehyde under the reaction conditions has been described above; this leads to the carboxylic acid itself.[21] Thus, eq 11 followed by eq 10 and then eq 12 produces the observed



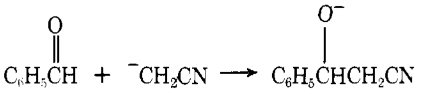
$$C_6H_5\overset{\overset{O}{\|}}{C}OO^- + C_6H_5\overset{\overset{O}{\|}}{C}H \longrightarrow 2C_6H_5CO_2^- + H^+ \qquad (12)$$

products. Together with the previously discussed oxidation of $C_6H_5CH_2OH$ we believe that this provides a reasonable rationalization of the processes that occur for the $O_2^-\cdot$ and C_6H_5CHO combination in pyridine (and by analogy, in benzene and other nonreactive solvents).

Benzaldehyde in Acetonitrile. The Cannizzaro reaction that occurs in inert solvents (eq 10) is generally a minor path in acetonitrile. Apparently, the base that is generated in the decomposition of $O_2^-\cdot$ (eq 11) is sufficiently basic to generate acetonitrile anion:

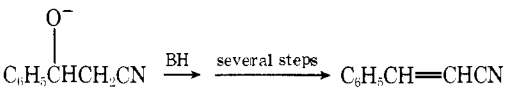
$$B^- + CH_3CN \rightleftharpoons BH + {}^-CH_2CN \qquad (13)$$

This species can then undergo condensation with benzaldehyde (eq 14). Protonation and loss of water lead to cinnamonitrile



$$C_6H_5\overset{\overset{O}{\|}}{C}H + {}^-CH_2CN \longrightarrow C_6H_5\overset{\overset{O^-}{|}}{C}HCH_2CN \qquad (14)$$

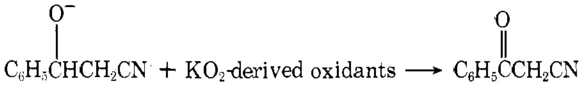
(eq 15). This process occurs efficiently with KOH, and to



$$C_6H_5\overset{\overset{O^-}{|}}{C}HCH_2CN \xrightarrow{BH} \xrightarrow{\text{several steps}} C_6H_5CH{=}CHCN \qquad (15)$$

varying extents with KO_2. The same condensation with KOH recently has been reported by Gokel and co-workers.[30]

With KO_2 present, there apparently is a competitive (to eq 15) oxidation of the β-hydroxynitrile condensation product (or its anion) to the ketone (eq 16), which is also a major product.



$$C_6H_5\overset{\overset{O^-}{|}}{C}HCH_2CN + KO_2\text{-derived oxidants} \longrightarrow C_6H_5\overset{\overset{O}{\|}}{C}CH_2CN \qquad (16)$$

This oxidation is slow for KO_2 alone (see benzyl alcohol oxidation above). The reaction mixture also generates O_2 and peroxide, which probably are the actual oxidants.

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