J. Am. Chem. Soc. **1983**, *105*, 7691–7696

Oxygenation by Superoxide Ion of CCl_4, $FCCl_3$, $HCCl_3$, p,p'-DDT, and Related Trichloromethyl Substrates ($RCCl_3$) in Aprotic Solvents

Julian L. Roberts, Jr., Thomas S. Calderwood, and Donald T. Sawyer*

Contribution from the Department of Chemistry, University of California, Riverside, California 92521. *Received April 22, 1983*

Abstract: In dimethylformamide (DMF) superoxide ion (O_2^-) oxygenates compounds with the trichloromethyl group: CCl_4, $HCCl_3$, and $FCCl_3$ yield bicarbonate ion; $PhCCl_3$ yields a mixture of $PhC(O)OO^-$ and $PhC(O)O^-$; CF_3CCl_3 and $HOCH_2CCl_3$ give their carboxylate anions, $RC(O)O^-$; and p,p'-DDT yields its dehydrochlorination product, DDE, which in turn reacts with O_2^- to give $(p\text{-ClPh})_2C{=}O$. Alkyl trichloromethyl compounds are unreactive with O_2^- within a 10-min reaction time at millimolar concentrations. The relative rates of reaction have been measured by the rotated ring–disc voltammetric method. On the basis of the relationship between the relative reaction rates and the electrophilic character of the substrates, as measured by the peak reduction potentials (E_p), the initial step is believed to be an electron transfer from the nucleophile to the electrophilic trichloromethyl group (a nucleophilic attack on chlorine with a concerted reductive displacement of Cl^- and formation of $RCCl_2OO\cdot$).

The chemical reactivity of superoxide ion (O_2^-) with a variety of substrates, especially in aprotic media, has been described in several recent reviews.[1-3] These provide ample evidence that O_2^- is an effective Bronsted base (able to abstract protons from weak oxygen and nitrogen acids (pK_a <25)) and a strong nucleophile toward esters and alkyl halides. It also is a moderate one-electron reducing agent for quinones, methyl viologen, sulfur dioxide, and oxidized transition-metal ions. Although there are numerous examples of the oxidation of reduced transition-metal ions by O_2^-, most purported oxidations of organic substrates occur via proton abstraction by O_2^- to give H_2O_2 and O_2, followed by electron transfer from substrate anion to O_2.

In a previous communication[4] we reported that superoxide ion rapidly degrades carbon tetrachloride, chloroform, dichloromethane, and p,p'-DDT. The present report describes more fully the reactivity of superoxide with these and related substrates that contain the trichloromethyl group ($RCCl_3$). For those compounds that react at a sufficiently rapid rate with O_2^- (apparent second-order rate constant >1 M^{-1} s^{-1}), the relative reaction rates, the principal reaction products, and the reaction stoichiometries have been determined. In most cases this has provided sufficient evidence to write a plausible net chemical reaction, but the identities of the intermediates of the primary and succeeding reaction steps remain unknown, except for p,p'-DDT where they are sufficiently stable to permit identification.

Experimental

Equipment. Conventional electrochemical instrumentation, cells, and electrodes were employed for the cyclic voltammetric and controlled potential Coulometric measurements.[5] A Vacuum Atmospheres Corp. inert atmosphere glovebox was used for the storage and preparation of solutions of tetramethylammonium superoxide. A Pine Instruments Co. Model RDE 3 dual potentiostat, Model PIR rotator, and glassy carbon or platinum ring–disc electrodes were used to make the kinetic measurements. Product species that contained an aromatic ring were identified by use of an Altex Model 330 isocratic liquid chromatograph with UV detection at 254 nm; the 250 × 4.6-mm stainless steel column was packed with 10-micron Merck Lichrosorb RP-2. A Finnigan Instruments Model 3200D glass capillary GC-MS system was used to separate and identify volatile reaction products. Proton NMR spectra were obtained with a Varian EM -390 spectrometer, ^{13}C NMR spectra with a JEOL Model FX-200 FT-NMR spectrometer, and ^{19}F NMR spectra with a Bruker WM500 FT-NMR. The infrared spectra for isolated solid products were recorded in a KBr matrix.

Chemicals and Reagents. Burdick and Jackson "distilled in glass" solvents were used as received for most of the experiments. When necessary, acetonitrile was further dried by passing it through a column of Woelm N Super I alumina. Ammonia used as a solvent was Matheson anhydrous grade. Tetraethylammonium perchlorate (TEAP) from G. Frederick Smith Chemical Co. was dried in vacuo and used as the supporting electrolyte (0.1 M TEAP) in the electrochemical experiments. Other reagents and substrates were analytical grade or highest purity available, and generally were used without further purification.

Methods. Controlled potential electrolytic reduction of O_2 at a platinum-mesh electrode was used to prepare solutions of O_2^-. The residual dioxygen was removed by bubbling with argon and the concentration of O_2^- was determined by anodic linear-sweep voltammetry. To such solutions a quantity of substrate was added which, on the basis of one or more trials, was sufficient to consume about 80% of the O_2^-. The unreacted O_2^- concentration was again measured by anodic voltammetry. These data provided the stoichiometric ratios for the quantity of O_2^- consumed per mole of substrate. In separate experiments a negative voltage sweep provided a measure of any dioxygen that was produced when stoichiometric amounts of the substrate and O_2^- were reacted.

Measurements of the rate of reaction of superoxide ion with various substrates were made with a rotated ring–disc electrode, usually glassy carbon. The pseudo-first-order rate constants (k_1) were determined by using the method described by Albery and Hitchman.[6]

The reaction products were characterized after stoichiometric amounts (at millimolar concentrations) of substrate and superoxide ion were combined. Solutions of O_2^- were prepared either by controlled potential (or current) electrolysis or by dissolution of weighed amounts of tetramethylammonium superoxide $[(Me_4N)O_2]$.[7] Aliquots (10 mL or 20 mL) of the reaction mixture, after dilution with 60–80 mL of water, were analyzed for base by pH titration with 0.05 M HCl, for chloride by potentiometric titration with 0.05 M $AgNO_3$, and for peroxides by an iodometric titration that allowed the independent measurement of organic peroxo acids and hydrogen peroxide.[8] Fluoride ion determinations were performed by direct potentiometry with a Beckman fluoride-specific electrode. The latter was calibrated by use of known amounts of F^- in the same medium.[9]

Evidence for a dichlorocarbene intermediate in the reactions of CCl_4 and $HCCl_3$ was sought by the addition of approximately 50 mg of solid $(Me_4N)O_2$ to a solution that contained 20 μL of substrate and 20 μL of 2,3-dimethyl-2-butene (Aldrich Chemical Co.) in 1 mL of Me_2SO. The reaction mixture was added to 10 mL of water, then 1 mL of substrate

---

(1) Sawyer, D. T.; Valentine, J. S. *Acc. Chem. Res.* **1981**, *14*, 393.

(2) Sawyer, D. T.; Gibian, M. J. *Tetrahedron* **1979**, *35*, 1471.

(3) Lee-Ruff, E. *Chem. Soc. Rev.* **1977**, *6*, 195.

(4) Roberts, J. L., Jr.; Sawyer, D. T. *J. Am. Chem. Soc.* **1981**, *103*, 712.

(5) Chin, D.-H.; Chiericato, G., Jr.; Nanni, E. J., Jr.; Sawyer, D. T. *J. Am. Chem. Soc.* **1982**, *104*, 1296.

(6) Albery, W. J.; Hitchman, M. L. "Ring-Disc Electrodes"; Clarendon Press: Oxford, 1971.

(7) Sawyer, D. T.; Calderwood, T. S.; Yamaguchi, K.; Angelis, C. T. *Inorg. Chem.* **1983**, *22*, 2577.

(8) (a) Ledaal, T.; Bernatek, E. *Anal. Chim. Acta* **1963**, *28*, 322. (b) Thornton, W. M., Jr.; Roseman, R. *Am. J. Sci.* **1930**, *220*, 14.

(9) Frant, M. S.; Ross, J. W., Jr. *Anal. Chem.* **1968**, *40*, 1169.

0002-7863/83/1505-7691$01.50/0

Table I. Stoichiometries and Kinetics for the Reaction of 0.1-5 mM O_2^- with Substituted Trichloromethyl Compounds in Dimethylformamide (0.1 M Tetraethylammonium Perchlorate) at 25 °C[a]

substrate [S] 1-10 mM	O_2^- per S	Cl^- released per S	O_2 released per S	base (pK_a) released per S	$k_1/[S]$, M^{-1} s^{-1}
CCl_4	5.0 ± 0.5	4.0 ± 0.2	3.3 ± 0.2	1.0 ± 0.2 (6.6)	$(3.8 \pm 1.0) \times 10^3$
$FCCl_3$	5.0 ± 0.5	3.0 ± 0.2	2.5 ± 0.2	1.0 ± 0.2 (6.6)	4.0 ± 1.0
$HCCl_3$	4.0 ± 0.4	3.0 ± 0.2	2.0 ± 0.2	1.0 ± 0.2 (6.6)	0.4 ± 0.2
CF_3CCl_3	4.0 ± 0.4	3.0 ± 0.2	2.4 ± 0.2	1.0 ± 0.2 (<3)	$(4.0 \pm 1.0) \times 10^2$
$PhCCl_3$	4.0 ± 0.4	3.0 ± 0.2	2.4 ± 0.2	1.0 ± 0.2 (4.7, 8.0)	$(5.0 \pm 1.0) \times 10^1$
CH_3CCl_3					<1
$HOCH_2CCl_3$	4.0 ± 0.4	3.0 ± 0.2		1.0 ± 0.2 (4.0)	$(4.7 \pm 1.0) \times 10^1$
$CH_3CH(OH)CCl_3$					<1
(p-ClPh)$_2$CHCCl$_3$ (p,p'-DDT)	1.0 ± 0.2	1.0 ± 0.1			$(1.0 \pm 0.2) \times 10^2$
(p-MeOPh)$_2$CHCCl$_3$ (Methoxychlor)	1.0 ± 0.2	1.0 ± 0.1			$(1.0 \pm 0.2) \times 10^1$
(p-ClPh)$_2$CFCCl$_3$ (F-DDT)	1.0 ± 0.2	1.0 ± 0.1			$(1.7 \pm 0.2) \times 10^2$
(p-ClPh)$_2$C=CCl$_2$ (DDE)	3.0 ± 0.3	2.0 ± 0.2		1.0 ± 0.2 (6.6)	2.0 ± 0.6

[a] Pseudo-first-order rate constants, k_1 (normalized to unit substrate concentration [S]), were determined from measurements with a glassy carbon-glassy carbon ring-disc electrode that was rotated at 900 rpm.

was added and the mixture shaken to extract the organic reaction products into the added CCl_4 or $HCCl_3$. After two 10-mL water washes, the organic layer was separated, dried with anhydrous $MgSO_4$, diluted 50-fold in H_2CCl_2, and analyzed by capillary GC-MS.

The rates of reaction of OH^- with compounds that contain the $-CCl_3$ group were investigated by the addition of an equimolar amount of tetrabutylammonium hydroxide (1 M in methanol) to a stirred solution of 1 mM substrate in 0.1 M TEAP/Me_2SO; the current for the reduction of substrate at a glassy carbon rotated disc electrode was recorded as a function of time.

Results

Reactivity of O_2^- with CCl_4 and $RCCl_3$ Compounds. Substrates that contain the $-CCl_3$ group bonded to an electron-withdrawing residue readily react with superoxide ion in aprotic solvents such as dimethylformamide (DMF) to yield chloride ion, dioxygen, oxo bases, and peroxo compounds. Table I summarizes the reaction stoichiometries for the combination of O_2^- with CCl_4, $FCCl_3$, $HCCl_3$, CF_3CCl_3, $PhCCl_3$, $HOCH_2CCl_3$, and p,p'-DDT and related $RCCl_3$ compounds.

When CCl_4, $FCCl_3$, and $HCCl_3$ are combined with a stoichiometric amount of electrogenerated superoxide ion in dimethylformamide (DMF) or dimethyl sulfoxide (Me_2SO), all of the chlorine and fluorine is quantitatively converted to chloride and fluoride (Table I). pH titrations of separate aliquots of the reaction mixtures (after dilution with water) confirm that the carbon atom of all three substrates is oxygenated to the same base, bicarbonate ion (pK_a of conjugate acid, 6.6).

In a prior communication the product of the reaction between $HCCl_3$ was identified incorrectly as peroxoformate.[4] New evidence clearly shows that the base is bicarbonate ion: (a) addition of excess perchloric acid followed by gentle bubbling with argon eliminates the base, i.e., back-titration with NaOH shows that only perchloric acid is present; (b) only hydrogen peroxide (and no peroxoformate) is present on the basis of an iodometric titration that discriminates between peracids and hydrogen peroxide.[8] If peroxoformate had been present in the reaction mixture, but had decomposed to formate ion, the measured pK_a would have corresponded to that of formic acid ($pK_a = 3.8$).

The stoichiometric yield of bicarbonate and three Cl^- ions from the combination of four O_2^- per $HCCl_3$ confirms that the C–H bond is broken during the course of the reaction. Addition of ca. 50 mg of solid $(Me_4N)O_2$ to 1 mL of 0.16 M 2,3-dimethyl-2-butene and 0.25 M $HCCl_3$ in Me_2SO gave a small yield (ca. 7% based on $HCCl_3$) of 1,1-dichloro-2,2,3,3-tetramethylcyclopropane (the :CCl_2 adduct).

In general, alkyl-substituted chloroform derivatives (such as CH_3CCl_3) are not reactive on the time scale of our experiments (less than 50% reaction in 1000 s at mM initial concentrations, which corresponds to an apparent second-order rate constant that is less than 1 M^{-1} s^{-1}). Substitution of a methyl group for a methylene hydrogen atom on 2,2,2-trichloroethanol reduces the reactivity to a negligible level.

pH titrations of the product solutions from the stoichiometric combination of O_2^- with CF_3CCl_3, $PhCCl_3$, and $HOCH_2CCl_3$ yield midpoint pH values (equivalent to apparent pK_a constants) that are consistent with those of $CF_3C(O)OH$, a mixture of $PhC(O)OOH$ and $PhC(O)OH$, and $HOCH_2C(O)OH$, respectively (Table I). The presence and yield of benzoate ion from the reaction of O_2^- with $PhCCl_3$ in DMF has been confirmed by HPLC analysis. The ^{19}F NMR spectrum also is consistent with the formation of $CF_3C(O)O^-$ (12.2-ppm shift relative to a $PhCF_3$ internal standard, compared to a 14.0-ppm shift for authentic $CF_3C(O)OH$ in the same medium; the difference is due to the anionic form).

The reaction of O_2^- with $PhCCl_3$ in DMF yields about 30% peroxobenzoate ion; the remainder of the product is benzoate ion. The other $RCCl_3$ compounds probably yield peroxo acid anions as the main product of the reaction with O_2^-, but upon dilution with water they rapidly hydrolyze to give H_2O_2 and the carboxylate anion.[10]

Reactivity of O_2^- with p,p'-DDT and Its Structural Analogues. Electrogenerated O_2^- in DMF rapidly dehydrochlorinates p,p'-DDT to give 2,2-bis(p-chlorophenyl)-1,1-dichloroethene (DDE). (While this work was in progress, an analogous reaction was reported to occur when 0.1 M p,p'-DDT in DMF was stirred with an equimolar amount of KO_2 for 1 h at 20 °C.)[11] Addition of O_2^- beyond a 1:1 mol ratio causes the DDE to be oxygenated further to 4,4'-dichlorobenzophenone.

$$p,p'\text{-DDT} \xrightarrow{O_2^-} \text{DDE} \xrightarrow{O_2^-} \text{4,4'-dichlorobenzophenone} \xrightarrow{O_2^-,\ H_2O} \text{4-chlorobenzoate} + \text{polar compounds} \quad (1)$$

Addition of excess O_2^- results in the formation of 4-chlorobenzoate ion and other unidentified polar compounds.

This sequence of reactions is observed when a sample of p,p'-DDT is placed in an electrochemical cell that contains DMF (0.1 M TEAP) saturated with oxygen and the O_2 is reduced to O_2^- by controlled potential electrolysis at a platinum mesh electrode. Each step of the reaction sequence (eq 1) has been confirmed by separate experiments with DDE and 4,4'-dichlorobenzophenone as starting materials. However, for rigorously dry solvent, O_2^- does not react at a significant rate with carefully purified 4,4'-dichlorobenzophenone.

Superoxide ion reacts with Methoxychlor [(p-MeOPh)$_2$CHCCl$_3$] via 1:1 stoichiometry to give the dehydrochlorination product, 2,2-bis(p-methoxyphenyl)-1,1-dichloroethane. This analogue of DDE is inert to further reaction with O_2^-. Apparently, the substitution of p-methoxyphenyl for p-chlorophenyl deactivates the dichloroethane group with respect to further superoxide attack.

2,2-Bis(p-chlorophenyl)-2-fluoro-1,1,1-trichloroethane (F-DDT) reacts with O_2^- in DMF or Me_2SO to form DDE. (The DDE

---

[10] Swern, D. "Organic Peroxides"; Swern, D., Ed.; John Wiley & Sons, Inc.: New York, 1970; Vol. I, pp 338–343.

[11] Dureja, P.; Casida, J. E.; Ruzo, L. O., *Tetrahedron Lett.* **1982**, 5003.

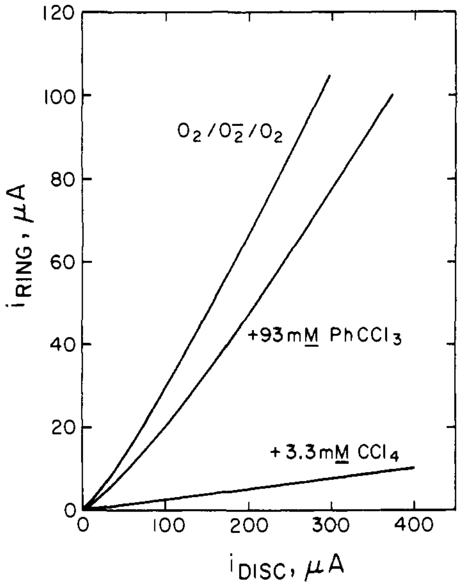


Figure 1. Ring–disc current traces for $O_2 \rightarrow O_2^-$ reduction (at the disc) and reoxidation of $O_2^- \rightarrow O_2$ (at the ring) for a rotated (900 rpm) glassy carbon ring–disc electrode in air-saturated 0.1 M tetraethylammonium perchlorate in dimethylformamide (DMF). The bulk O_2 concentration is ca. 1 mM. The slope of the ring–disc current trace is equal to the collection efficiency, which decreases when a substrate that reacts with O_2^- is added. This is shown for α,α,α-trichlorotoluene ($PhCCl_3$) and CCl_4. Pseudo-first-order rate constants are obtained from a working curve of collection efficiency vs. a dimensionless rate parameter (see ref 6 for details).

reaction product has been confirmed by proton, ^{13}C, and ^{19}F NMR, by HPLC, and by infrared and mass spectrometry.) The subsequent course of the reaction is complex, and the fate of the fluorine is unknown. Fluoride ion measurements with a specific ion electrode indicate that less than 5% of the original fluorine is present as free F^-. Control experiments confirm that F^- does not react rapidly with DDE, but that it does react with 4,4′-dichlorobenzophenone (a product that results from the reaction of DDE and O_2^-).

Reactivity of Hydroxide Ion with $RCCl_3$ Compounds. A previous study has determined (via competitive rate measurements) that hydroxide ion reacts rapidly with CCl_4 and $HCCl_3$ in Me_2SO;[4] the apparent second-order rate constant is about 10^3 M^{-1} s^{-1} for the CCl_4/OH^- reaction. The rates for reaction of OH^- with $FCCl_3$, $HCCl_3$, CF_3CCl_3, $PhCCl_3$, CH_3CCl_3, and *p,p′*-DDT are so rapid that the rate parameters cannot be evaluated by conventional pseudo-first-order decay methods. When the concentrations of substrate and OH^- are each ca. 1 mM the reactions are complete within the time of mixing (ca. 1 s), which implies that the apparent second-order rate constants for each substrate are greater than 500 M^{-1} s^{-1}.

Combination of 1 equiv of OH^- with *p,p′*-DDT yields DDE, which is the expected dehydrochlorination product. DDE in turn reacts with a second hydroxide ion, but the reaction is sufficiently slow to follow its rate by mixing millimolar concentrations of DDE with hydroxide ion in Me_2SO. Periodic removal of samples (quenched by a tenfold dilution in methanol) and anlysis by reverse-phase HPLC gives two product peaks with retention times that are less than that for DDE, but greater than that for 4,4′-dichlorobenzophenone (the primary product from the reaction of superoxide ion with DDE). The reaction products derived from reaction of OH^- with DDE and the $RCCl_3$ compounds have not been identified and are the subject of current investigations. Dimethylformamide was not used as a solvent because it is hydrolyzed by hydroxide ion.[12]

Kinetic Measurements. Figure 1 illustrates typical ring–disc current traces for the $O_2/O_2^-/O_2$ reduction and reoxidation cycle

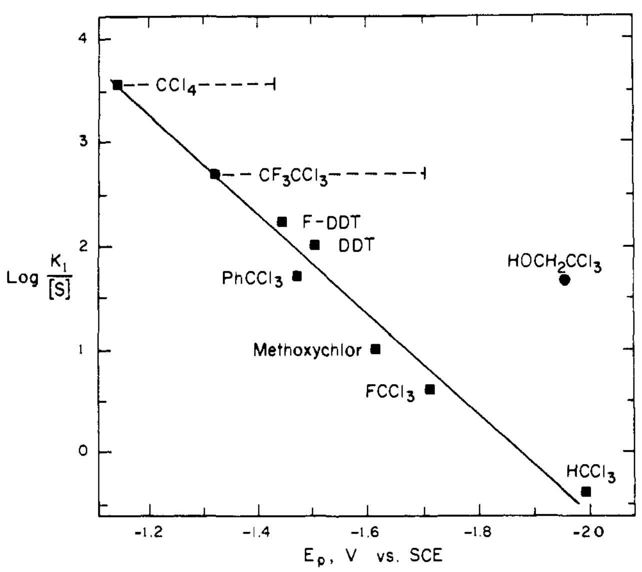


Figure 2. A plot of the logarithm of the normalized pseudo-first-order rate constants (for the reactions of O_2^- with compounds in Table I) vs. the peak reduction potentials, E_p (volts vs. aqueous SCE), for the first cathodic peak of the compounds. The straight line is a linear least-squares fit (slope = 4.9 V^{-1}) to the data points represented by small squares (the point for 2,2,2-trichloroethanol is not included in the data set). The peak reduction potentials were obtained at a stationary glassy carbon electrode in argon-saturated 0.1 M tetraethylammonium perchlorate in dimethylformamide (sweep rate, 0.1 V s^{-1}).

in the absence and presence of reactive substrates. (The collection efficiencies are equal to the slopes of the traces.) The kinetic data that are derived from these and related traces from the voltammetric rotated ring–disc method for the reaction of O_2^- with several substrates are summarized in Table I. The rate parameters are presented as apparent second-order rate constants and have been obtained by dividing the pseudo-first-order rate constants by the substrate concentration. Although the ring–disc method has given results which are in good agreement with kinetic measurements made by independent methods,[13] it has not previously been applied to complex multi-step reactions of the type reported here. The method gives reproducible relative rate measurements, but the normalized constants should not be interpreted as accurate absolute second-order rate constants. The stoichiometries and rates of the reactions that follow the primary step cannot be readily evaluated. Thus, for infinitely fast subsequent steps the normalized pseudo-first-order rate constant should be divided by the overall O_2^--per-substrate stoichiometry to obtain the correct second-order rate constant for the primary reaction. However, under the pseudo-first-order conditions of the ring–disc measurements, the subsequent steps may be limited by the available concentrations of intermediate and O_2^-.

In a typical experiment the local superoxide ion concentration in the vicinity of the disc is about 1 mM and the substrate concentration is at least tenfold larger. For most substrates the calculated pseudo-first-order rate constants increase linearly with substrate concentration and are nearly independent of rotational speed (for 2,2,2-trichloroethanol the apparent second-order rate constant increases from 47 to 87 M^{-1} s^{-1} as the rotational speed is increased from 900 to 2500 rpm). The apparent second-order rate constants of Table I are for a rotational speed of 900 rpm.

---

(12) (a) Buncel, E.; Kesmarky, S.; Symons, E. A. *Chem. Commun.* **1971**, 120. (b) Buncel, E.; Symons, E. A. *Ibid.* **1970**, 164.

(13) The accuracy of kinetic measurements made with the ring–disc electrode was tested by comparison with measurements of the reaction rate of KO_2 with *n*-BuBr in Me_2SO by stopped flow spectrophotometry (Danen, W. C.; Warner, R. J. *Tetrahedron Lett.* **1977**, 989). A value of 150 M^{-1} s^{-1} for the second-order rate constant was obtained from the measured pseudo-first-order rate constant by use of the expression $k_2 = k_1/2(S)$. For psuedo-first-order conditions and the same stoichiometric factor of 2, we obtained apparent second-order rate constants of 170 M^{-1} s^{-1} with a platinum ring–disc electrode with thin-gap, thin-ring geometry, and 150 M^{-1} s^{-1} with a glassy carbon electrode with wide-gap, wide-ring geometry for the reaction of O_2^- with *n*-BuBr in 0.1 M TEAP/Me_2SO.

Reduction Potentials of CCl_4 and $RCCl_3$ Compounds. Figure 2 illustrates, for the substrates of Table I, the correlation between the logarithm of the apparent second-order rate constants and the electrochemical reduction potentials of the substrates (E_p (V) vs. aqueous SCE, at a glassy carbon electrode; sweep rate, 0.1 V/s in 0.1 M TEAP/DMF). The point for 2,2,2-trichloroethanol is not included in the data set for the points that lie along the straight line. For some compounds, such as CCl_4 and CF_3CCl_3, the position and shape of the first peak are dependent on the pretreatment of the electrode. Where there is a differrence between the reduction potentials on glassy carbon and platinum, the peak potential at glassy carbon is more positive. With slow scan rates an anodic peak is not observed when the scan direction is reversed, except for the two –OH-substituted compounds where an oxidation wave is observed on platinum. The absence of an anodic peak indicates that the electron-transfer step is followed by a rapid chemical step (probably expulsion of Cl^-).[14]

Discussion and Conclusions

CCl_4 and $FCCl_3$. The stoichiometric data in Table I for CCl_4 and $FCCl_3$ are consistent with an overall net chemical reaction that, in each case, yields bicarbonate ion.

$$CCl_4 + 5O_2^- + H_2O \rightarrow HOC(O)O^- + 4Cl^- + {}^7/_2O_2 + {}^1/_2H_2O_2 \quad (2)$$

Because the solvents used normally contain millimolar concentrations of water and because the reaction mixtures are diluted with water before analysis, the bicarbonate ion and hydrogen peroxide may result from hydrolysis of precursor products. The formal anhydride of bicarbonate ion and hydrogen peroxide (2:1 mol ratio) is peroxodicarbonate, $C_2O_6^{2-}$, which is produced by reaction of O_2^- with CO_2 in aprotic solvents.[15]

$RCCl_3$ Compounds. When O_2^- reacts with $RCCl_3$ compounds, the R–C bond is not cleaved. For $PhCCl_3$, CF_3CCl_3, and $HOCH_2CCl_3$, the reaction stoichiometry is represented by

$$RCCl_3 + 4O_2^- + H_2O \rightarrow RC(O)O^- + 3Cl^- + {}^5/_2O_2 + H_2O_2 \quad (3)$$

The fact that $PhCCl_3$ gives a 30% yield of peroxobenzoate indicates that its reaction stoichiometry before dilution with water probably is representative of the group and produces the peracid anion

$$RCCl_3 + 4O_2^- \rightarrow RC(O)OO^- + 3Cl^- + {}^5/_2O_2 \quad (4)$$

The latter species is rapidly hydrolyzed by trace water to give the carboxylate and H_2O_2.[10]

$$RC(O)OO^- + H_2O \rightleftharpoons RC(O)O^- + H_2O_2 \quad (5)$$

Thus, eq 3 represents the sum of eq 4 and 5.

The results for the reaction of O_2^- with CCl_4 and with $RCCl_3$ compounds indicate that these reactions belong to the class of nucleophile–substrate reactions which are initiated by a single electron transfer (SET) from the electron-donor O_2^- to the $-CCl_3$ electron-acceptor group. The process is believed to involve nucleophilic attack by O_2^- on chlorine, followed by a concerted displacement of Cl^- and formation of RCOO·. The electron-transfer reduction of alkyl halides and CCl_4 is well documented.[16] Likewise, the SET mechanism is now well established and has been amply reviewed.[17-19] There also has been a recent report that an analogous reaction, that of thiophenoxide with compounds of the type CF_2BrX (X = Cl, Br), is initiated by an electron transfer from PhS^- to the alkyl halide.[20]

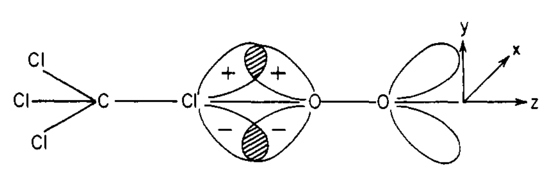


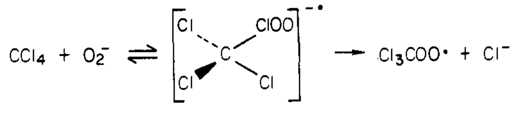
Figure 3. A schematic representation of the overlap of the partially filled π^* antibonding orbitals of O_2^- with the empty d orbitals of a chlorine atom. The internuclear axis is taken as the z axis. The $\pi^*_{yz} \rightarrow d_{yz}$ overlap is shown, and there is an equivalent $\pi^*_{xz} \rightarrow d_{xz}$ overlap. This is analogous to the bonding proposed in transition-metal–carbonyl complexes (d → π^*), but in the reverse sense.

The viability of our argument that the primary step is an electron transfer rests on the plausibility of electron transfer between O_2^- and CCl_4 (or $R-CCl_3$) and the implausibility of direct nucleophilic attack of O_2^- upon the carbon atom of the –CCl group. We address first the question of electron transfer.

The measured peak potentials for reduction of $RCCl_3$ compounds are more negative than the reduction potential for O_2 ($E^{\circ\prime}$, –0.75 V vs. SCE) in DMF (see Figure 1), which implies that the free-energy change for electron transfer is endergonic. Both theoretical and experimental analyses of electron transfer in the endergonic region yield reaction rates[21-23] that are comparable to those of Table I; the latter exhibit a similar dependence on the E_p values for the acceptor molecules (Figure 1). For example, the reported slopes for similar plots vary between 3 and 12.7 V^{-1};[21,24] the slope for the curve of Figure 2 is 4.9 V^{-1}.

The data point for 2,2,2-trichloroethanol shown in Figure 2 indicates a reaction rate that is about 100 times faster than would be expected on the basis of its reduction potential, E_p. This and the fact that an anodic peak is observed on platinum when the scan is reversed indicate that 2,2,2-trichloroethanol can act as a weak acid, with O_2^- deprotonating the –OH group as well as attacking the $-CCl_3$ group. (The anodic peak that is observed on a reverse scan at a platinum electrode is due to the oxidation of the hydrogen that is produced from proton reduction during the forward scan.) Substitution of a $-CH_3$ group for a hydrogen atom in 2,2,2-trichloroethanol apparently reduces both the acidity of the –OH group and the electrophilic character of the $-CCl_3$ group because $CH_3CH(OH)CCl_3$ reacts slowly with O_2^-.

The four chlorine atoms of CCl_4 present such a formidable steric barrier that direct attack by O_2^- upon the carbon atom must be ruled out. Instead, there must be some form of interaction (weak orbital overlap) between O_2^- and electrophilic chlorine atoms as illusted by Figure 3. The resulting activated complex can then dissociate to give chloride ion, dioxygen, and $\cdot CCl_3$, with subsequent coupling of the $\cdot CCl_3$ radical and O_2 in the solvent cage to form $Cl_3COO\cdot$, a process reported to be fast.[25]



(6)

The much slower rates (about an order of magnitude) for the reactions of O_2^- with CCl_4 and $RCCl_3$ in acetonitrile (MeCN) relative to those in DMF (Table I) and Me_2SO probably are due

---

[14] Karrenbrock, F.; Schafer, H. J. *Tetrahedron Lett.* **1978**, 1521.

[15] Roberts, J. L., Jr.; Calderwood, T. S.; Sawyer, D. T., *J. Am. Chem. Soc.*, submitted.

[16] Eberson, L. *Acta Chem. Scand., Ser. B* **1982**, *B36*, 533.

[17] Kornblum, N. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 734.

[18] Bunnett, J. F. *Acc. Chem. Res.* **1978**, *11*, 413.

[19] (a) Chanon, M. *Bull. Chim. Soc. Fr.* **1982**, II-197. (b) Chanon, M.; Tobe, M. L. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 1.

[20] Rico, I.; Cantacuzene, D.; Wakselman, C. *J. Org. Chem.* **1983**, *48*, 1979.

[21] Scandola, F.; Balzani, V.; Schuster, G. B. *J. Am. Chem. Soc.* **1981**, *103*, 2519.

[22] Andrieux, C. P.; Blockman, C.; Dumas-Bouchiat, J.-M.; Saveant, J.-M. *J. Am. Chem. Soc.* **1979**, *101*, 3431.

[23] Klingler, R. J.; Kochi, J. K. *J. Am. Chem. Soc.* **1982**, *104*, 4186.

[24] In a study of the electron transfer between halobenzenes and a number of one-electron donor-anion radicals,[23] the second-order rate constants for chlorobenzene range from 3 M^{-1} s^{-1} to 2 × 10^4 M^{-1} s^{-1} in the endergonic free energy region. The potential differences ($E^\circ_{PhCl} - E^\circ_{donor}$) that correspond to these rate constants range from –0.54 to –0.24 V endergonic; the slope of the log k vs. E°_{donor} data is 12.7 V^{-1}.

[25] (a) Packer, J. E.; Slater, T. F.; Willson, R. L. *Life Sci.* **1978**, *23*, 2617. (b) Slater, T. F. In "Free Radicals, Lipid Peroxidation and Cancer"; McBrien, D. C. H., Slater, T. F., Eds.; Academic Press, Inc.: New York, 1982.

to the extremely weak solvation by MeCN of anionic leaving groups. This would favor the back reaction from the O_2^-/CCl_4 complex (eq 6) and retard the net reaction rate.

$HCCl_3$. The stoichiometry in Table I for the reaction of O_2^- with chloroform is consistent with eq 7. However, the reaction

$$HCCl_3 + 4O_2^- + H_2O \rightarrow HOC(O)O^- + 3Cl^- + 2O_2 + H_2O_2 \quad (7)$$

of $HCCl_3$ in a solution that contains electrogenerated O_2^- is much faster (half-reaction time of seconds) than predicted from the measured ring–disc reaction rate. Because O_2^- is produced in a small region at the disc and transported within a few milliseconds to the ring, there is not time to produce significant quantities of OH^- (or HO_2^-) by the decomposition reaction that can occur in a bulk solution of superoxide ion that contains small amounts of water:

$$2O_2^- + H_2O \rightarrow HO_2^- + OH^- + O_2 \quad (8)$$

The discrepancy between the bulk and ring–disc reaction rates implies that the primary reaction of $HCCl_3$ in solutions of electrogenerated O_2^- is not attack by O_2^- on the $-CCl_3$ group (or deprotonation by O_2^-), but deprotonation by the OH^- that results from the hydrolysis reaction of eq 8. This results in a net dehydrochlorination and formation of dichlorocarbene.[26]

$$OH^- + HCCl_3 \rightarrow [:CCl_3^- + H_2O] \rightarrow :CCl_2 + H_2O + Cl^- \quad (9)$$

The sum of eq 8 and 9 gives reaction 10 which represents the net reaction catalyzed by trace water:

$$HCCl_3 + 2O_2^- \xrightarrow{H_2O} :CCl_2 + Cl^- + HO_2^- + O_2 \quad (10)$$

The dichlorocarbene that is produced reacts further with O_2^- or solvent. The observed reaction stoichiometry of Table I (eq 7) requires a net stoichiometry given by

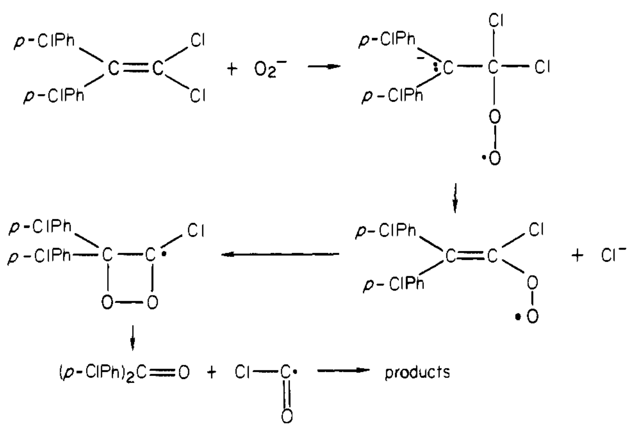
$$:CCl_2 + 2O_2^- + HO_2^- + H_2O \rightarrow HOC(O)O^- + 2Cl^- + O_2 + H_2O_2 \quad (11)$$

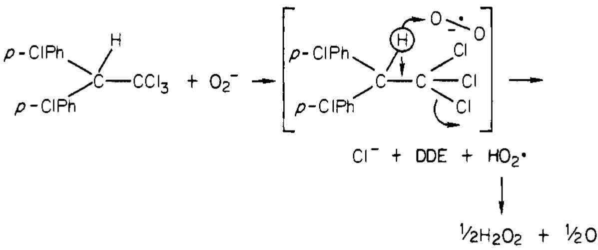
Dichlorocarbene also reacts with Me_2SO solvent to yield Me_2S and phosgene, $COCl_2$,[27] which in turn reacts rapidly with O_2^-.[28]

The dichlorocarbene-trapping experiment[29] confirms that some dichlorocarbene is formed, but does not prove that O_2^- deprotonates $HCCl_3$ to form the dichlorocarbene. For conditions where some OH^- is formed by reaction 8, the ring–disc measurements and the OH^- kinetic measurements indicate that the rate for the $O_2^-/HCCl_3$ reaction is at least 10^3 times slower than the reaction rate of OH^- with $HCCl_3$. This leads us to conclude that the bulk reaction is initiated by deprotonation of $HCCl_3$ by OH^-, not O_2^-. Similar conclusions may apply to the reported reaction of KO_2 with $HCCl_3$ in benzene.[30]

***p,p'*-DDT.** Both *p,p'*-DDT and Methoxychlor are rapidly deprotonated by OH^- with subsequent elimination of Cl^- to form the dehydrochlorination products. The same products are formed in their reactions with O_2^-. Because the reaction rates that are measured by the ring–disc electrode method are fairly rapid, the primary step must be a direct reaction with O_2^-, and not with OH^- that is produced by reaction of O_2^- with trace water in the solvent. This indicates that the initial reaction with O_2^- is deprotonation followed by elimination of Cl^-.

Scheme I





(12)

However, a note of caution is appropriate because several facts do not fit neatly into this interpretation: (a) There are at this time no well-documented examples of rapid deprotonation of carbon acids by O_2^-; (b) DDE, the dehydrochlorination product, also is the main product in the reaction of F-DDT with O_2^-, a reaction which cannot proceed by deprotonation because the hydrogen atom has been replaced by fluorine; (c) both the *p,p'*-DDT and F-DDT points fall on the straight line that correlates reaction rates and reduction potentials, consistent with the nucleophilic electron-transfer mechanism (see Figure 2). These facts support the nucleophilic electron-transfer mechanism rather than deprotonation as the primary step.

A plausible mechanism for the reaction of DDE (produced by dehydrochlorination of *p,p'*-DDT) is an initial nucleophilic addition of superoxide ion on the carbon atom that bears the chlorine atoms, followed by elimination of Cl^- and cyclization of the radical, which then decomposes to a chloroacyl radical and 4,4'-dichlorobenzophenone (Scheme I).[31] The chloroacyl radical can undergo subsequent facile reactions with O_2^- to give bicarbonate and chloride ions.[32]

On the basis of the reaction stoichiometries of Table I, the overall reaction of DDE with O_2^- in DMF that contains 5 mM H_2O is

$$(p\text{-ClPh})_2C{=}CCl_2 + 3O_2^- + H_2O \rightarrow (p\text{-ClPh})_2C{=}O + HOC(O)O^- + 2Cl^- + {}^1/{}_2H_2O_2 + O_2 \quad (13)$$

We did not observe any evidence for nucleophilic substitution of the aromatic halides of 4,4'-dichlorobenzophenone by O_2^- to give the coresponding phenol, which is in contrast with the results reported for 4-chlorobenzophenone.[33]

Because we expected F-DDT to react with O_2^- in a manner analogous to that of trichloromethyl compounds of the $RCCl_3$ type, formation of DDE as the major product was surprising and requires a unique mechanism. The fluorine atom was not found as free F^-, but it appears to react with the solvent or some other

---

(26) Regen, S. L.; Singh, A. *J. Org. Chem.* **1982**, *47*, 1587 and references therein.

(27) Oda, R.; Mieno, M.; Hayashi, Y. *Tetrahedron Lett.* **1967**, 2363.

(28) A preliminary value of $k_1/[S] \sim 4 \times 10^3$ M^{-1} s^{-1} has been obtained for the reaction of $COCl_2$ with O_2^- in 0.1 M TEAP/CH_3CN by use of a glassy carbon ring–disc electrode.

(29) 2,3-Dimethyl-2-butene has been chosen as the dichlorocarbene trapping agent because it traps dichlorocarbene more efficiently than other alkenes, e.g., cyclohexane.[26]

(30) Purrington, S. T.; Kenion, G. B. *J. Chem. Soc., Chem. Commun.* **1982**, 731.

(31) Kochi, J. K. "Free Radicals"; Kochi, J. K., Ed.; John Wiley & Sons, Inc.: New York, 1973; p 698.

(32) Calderwood, T. S.; Neuman, R. C., Jr.; Sawyer, D. T. *J. Am. Chem. Soc.* **1983**, *105*, 3337.

(33) Gareil, M.; Pinson, J.; Saveant, J. M. *Nouv. J. Chim.* **1981**, *5*, 311.

organic component. The net overall process may involve an activated complex that is similar to that for *p,p'*-DDT (see eq 12).

$$(p\text{-ClPh})_2CFCCl_3 + O_2^- \xrightarrow{RH} (p\text{-ClPh})_2C{=}CCl_2 + Cl^- + {}^1/_2H_2O_2 + {}^1/_2O_2 + RF \quad (14)$$

The ring–disc results from $HCCl_3$ (and possibly for *p,p'*-DDT and Methoxychlor) clearly show that superoxide ion is not as effective as OH^- for the deprotonation of a carbon acid. This might be expected because superoxide ion does not react with benzaldehyde, but OH^- does,[34] and O_2^- is a weak base in water (pK_a of $HO_2\cdot = 4.7$). However, O_2^- is an effective strong Brønsted base for the deprotonation of oxygen and nitrogen acids via its facile proton-induced disproportionation to H_2O_2 and O_2.[2] In general, proton exchange on carbon acids is much slower than exchange on oxygen or nitrogen acids, which reflects the generally higher activation energies for deprotonation of carbon acids.[35,36] Therefore, deprotonation of carbon acids is controlled more by kinetic factors than by equilibrium thermodynamics, and O_2^- is a less effective base than OH^- for such acids.

Acknowledgment. This work was supported by the National Science Foundation under Grant No. CHE-8212299. We also thank Professor Charles Wilkins and Ms. Carolyn Johlman for their assistance with the mass spectral analyses, Dr. Luciano Mueller of The Southern California Regional NMR Facility (NSF–supported at the California Institute of Technology) for his assistance with the ^{19}F NMR spectral determinations, Professor T. Roy Fukuto for a gift of a sample of F-DDT, and Professor Robert C. Neuman, Jr., for helpful discussions.

Registry No. O_2, 7782-44-7; O_2^-, 11062-77-4; CCl_4, 56-23-5; $FCCl_3$, 75-69-4; $HCCl_3$, 67-66-3; CF_3CCl_3, 354-58-5; $PhCCl_3$, 98-07-7; CH_3CCl_3, 71-55-6; $HOCH_2CCl_3$, 115-20-8; $CH_3CH(OH)CCl_3$, 76-00-6; $(p\text{-}ClC_6H_4)_2CHCCl_3$, 50-29-3; $(p\text{-}MeOC_6H_4)_2CHCCl_3$, 72-43-5; $(p\text{-}ClC_6H_4)_2CFCCl_3$, 1545-65-9; $(p\text{-}ClC_6H_4)_2C{=}CCl_2$, 72-55-9; $(Me_4N)O_2$, 3946-86-9; $:CCl_2$, 1605-72-7; OH^-, 14280-30-9; 2,3-dimethyl-2-butene, 563-79-1.

---

(34) Gibian, M. J.; Sawyer, D. T.; Ungermann, T.; Tangpoonpholvivat, R.; Morrison, M. M. *J. Am. Chem. Soc.* **1979**, *101*, 640.

(35) Crooks, J. E. "Proton-Transfer Reactions"; Caldin, E., Gold, V., Eds.; Chapman & Hall, Ltd.: London (Wiley: New York), 1975; Chapter 6.

(36) Reutov, O. A.; Beletskaya, I. P.; Butin, K. P. "CH-Acids"; Pergammon Press: New York, 1978.

Diels–Alder Reactions of 1-Azadienes[1]

Yea-Shun Cheng, Andrew T. Lupo, Jr., and Frank W. Fowler*

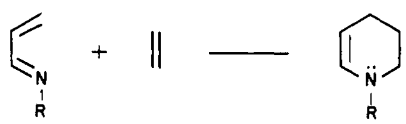
Contribution from the Department of Chemistry, State University of New York at Stony Brook, Stony Brook, New York 11794. *Received April 8, 1983*

Abstract: *N*-Acyl-1-azadienes have been prepared by the thermal elimination of acetic acid from *o*-acetylhydroxylamine derivatives. These reactive compounds have been observed to undergo the intramolecular Diels–Alder reaction to give piperidine derivatives. Studies on substituted azadienes suggest that the reaction follows predominantly an exo stereochemical pathway.

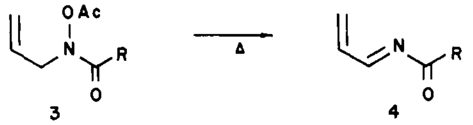
The incorporation of the Diels–Alder reaction into a synthetic scheme for the preparation of carbocyclic rings has proven to be a powerful strategy in total synthesis. This is because in one step two carbon–carbon bonds are formed with potential control of stereochemistry at all four of the newly created tetrahedral centers. Few reactions can rival the Diels–Alder reaction in this respect.

Piperidine derivatives are a common structural feature in many goal compounds and, in principle, the Diels–Alder reaction can also be applied to the preparation of these nitrogen heterocycles[2] by substitution of one of the carbon atoms of the reacting π system by nitrogen. The use of imines as dienophiles is well documented,[3] and the intramolecular version of this reaction has been effectively applied to the preparation of alkaloids.[4] Nitrogen-containing dienes are less common although the Diels–Alder reaction of 1- and 2-azadienes has been reported.[2] The Diels–Alder reaction of 1-azadienes, in principle, is particularly valuable for the synthesis of nitrogen heterocycles (Scheme I). Not only is a six-membered ring formed with potential control of stereochemistry at the tetrahedral centers but the product is an endocyclic enamine derivative. Because enamines are valuable for further structural elaboration[5] and are often postulated as key intermediates in alkaloid biosynthesis,[6] general methods for the preparation of

Scheme I



Scheme II



---

(1) A portion of this work has previously appeared as a communication to the editor: Cheng, Y.-S.; Fowler, F. W.; Lupo, A., Jr. *J. Am. Chem. Soc.* **1981**, *103*, 2090.

(2) (a) Wollweber, H. *Methoden. Org. Chem.* (*Houben*-Weyl) **1970**, *Teil 3*, 1128–1137. (b) Hamer, J. "1,4-Cycloaddition Reactions"; Hamer, J., Ed.; Academic Press: New York, 1967. (c) Arbuzov, Y. A. *Russ. Chem. Rev.* (*Engl. Transl.*) **1964**, *33*, 407. (d) Onishenko, A. S. "Diene Synthesis"; Israel Program for Scientific Translators: Jerusalem, 1964. (e) Sauer, J. *Angew. Chem., Int. Ed. Engl.* **1966**, *5*, 211. (f) Needleman, S. B.; Changkuo, M. C. *Chem. Rev.* **1962**, *62*, 405. For a recent example see: Sainte, F.; Serckx-Poncin, B.; Hesbain-Frisque, A. M.; Ghosez, L. *J. Am. Chem. Soc.* **1982**, *104*, 1428.

(3) (a) Weinreb, S. M.; Levin, J. I. *Heterocycles* **1979**, *12*, 949. (b) Weinreb, S. M.; Staib, R. R. *Tetrahedron* **1982**, *38*, 3087.

(4) (a) Khatri, N. A.; Schmitthenner, H. F.; Shringarpure, J.; Weinreb, S. M. *J. Am. Chem. Soc.* **1981**, *103*, 6387. (b) Gobao, R. A.; Bremmer, M. L.; Weinreb, S. M. *Ibid.* **1982**, *104*, 7065. (c) Bremmer, M. L.; Weinreb, S. M. *Tetrahedron Lett.* **1983**, 261.

(5) (a) Kuehne, M. E. *Synthesis* **1970**, 510. (b) "Enamines: Synthesis, Structure and Reactions"; Cook, A. G., Ed.; Marcel Dekker: New York, 1969.

(6) Cordell, G. A. "Introduction to Alkaloids: A Biosynthetic Approach"; Wiley-Interscience: New York, 1981.

0002-7863/83/1505-7696$01.50/0