the solution became blue. Dimethyl sulfide (4.2 mL) was immediately added, and the solution was stirred for 2 h at room temperature. The solvent was removed in vacuo, and the residue was passed through a mixed-bed ion exchanger (40 g) (M:MC, 1:1). The product obtained was purified further on silica (M:MC:W, 10:10:0.5) to furnish ketone **19** (0.84 g, 60%) as a white solid: TLC (M:MC:W, 10:10:1, B) R_f 0.22; NMR ($CDCl_3$, 500 MHz) δ 0.88 (t, 6 H), 1.29 (br s, 14 H), 1.57 (m, 4 H), 2.27 (t, 3 H), 2.39 (t, 2 H), 2.51 (m, 3 H), 3.38 (s, 9 H), 3.80 (m, 4 H), 3.97 (dd, 1 H), 4.19 (dd, 1 H), 4.30 (br s, 2 H).

Octanoic Acid, (*R,*R**)- and (*R**,*S**)-2-[[[(2-Trimethylamino)ethoxy)hydroxyphosphinyl]oxy]methyl]-4-hydroxydecyl Ester (20).** Ketone **19** (41.9 mg, 0.81 mmol) in absolute ethanol (4 mL) was reduced with $NaBH_4$ (5.0 mg, 0.13 mmol) by stirring 1.5 h at room temperature. The ethanol was removed in vacuo, and the residue was purified as described for **41** with use of 4 g of ion exchanger to give **20** (35 mg, 83%) as a white solid: TLC (same as **41**) R_f 0.20; NMR ($CDCl_3$, 500 MHz) δ 0.88 (br t, 6 H), 1.27 (br s, 16 H), 1.40-1.68 (m, 6 H), 2.25 (m, 3 H), 3.37 (s, 9 H), 3.80 (m, 4 H), 4.02 (m, 1 H), 4.16 (m, 1 H), 4.31 (br m, 2 H).

2-(Methylenenonyl)propanedioic Acid, Dimethyl Ester (73). This compound was made in an identical manner as **72**: bp (105-110 °C, 0.3 mm); TLC (10% E in P, B) R_f 0.38.

4-Methyleneundecanol (74). Diester **73** was partially saponified and decarboxylated as described.[33] The ester was reduced with $LiAlH_4$ in ether by using the standard procedure to give alcohol **74** (60%, overall): TLC (20% E in P, B) R_f 0.20.

Phosphoric Acid, 4-Methyleneundecyl 2-(Trimethylamino)ethyl Ester (75). Alcohol **74** (0.87 g) was phosphorylated and reacted with trimethylamine as described for **18** to give **75** (69%). The product was purified on silica (M:MC:W, 20:20:1): TLC (same solvent, B) R_f 0.24; NMR ($CDCl_3$, 300 MHz) δ 0.88 (t, 3 H), 1.25 (s, 8 H), 1.48 (br t, 2 H), 1.60-1.75 (m, 2 H), 1.85-2.08 (m, 4 H), 3.30 (s, 9 H), 3.75 (br m, 2 H), 3.95 (br s, 2 H), 4.25 (br m, 2 H), 4.68 (s, 1 H), 5.10 (br t, 1 H).

Phosphoric Acid, 4-Oxoundecyl 2-(Trimethylamino)ethyl Ester (25). Olefin **75** (0.5 g) was reacted with ozone as described for **19** to give the ketone (0.25 g, 50%) after purification on a mixed-bed ion exchanger (M:MC, 1:1) and on silica (M:MC:W, 20:20:1): TLC (same solvent, B) R_f 0.24; NMR ($CDCl_3$, 500 MHz) δ 0.88 (t, 3 H), 1.25 (s, 8 H), 1.53 (t, 2 H), 1.85 (t, 2 H), 2.40 (t, 2 H), 2.50 (t, 2 H), 3.39 (s, 9 H), 3.80-3.90 (m, 4 H), 4.32 (br s, 2 H).

Biological Methods. The phospholipase assays were carried out in a pH-stat as described previously.[34] The required amounts of DPPC and inhibitor were transferred to glass tubes from stock solutions in methanol/chloroform (1:1). The solvent was removed with a stream of argon, and 1 mL of a solution containing Triton X-100 (40 mM) and $CaCl_2$ (10 mM) in quartz-distilled water was added. The tubes were sonicated at 40 °C for several minutes to solubilize the lipids. Assays were conducted in a pH-stat by placing the reaction mixture into a small glass tube containing a magnetic stir bar and a side arm fitted with a rubber septum. A small diameter pH electrode was inserted through the top, and a stream of argon was passed over the solution to prevent CO_2 absorption. The tube was immersed in a water bath at 40 ± 0.2 °C, and the solution was continuously stirred. The pH of the reaction mixture was adjusted to approximately 8.5 with 0.1 N NaOH, and enzyme (amounts given in figure legends) was added. The pH was allowed to drop to 8.0 and held near this value (±0.1 pH units) by continuous addition of 0.01 N NaOH from a Hamilton syringe inserted directly into the solution through the rubber septum. The amount of base added over 2-3 min was recorded. Measurements were repeated two to three times and were found to be reproducible within 15%. CMC values for the phospholipid analogues were determined as described.[35]

Acknowledgment. The generous support of this research by the National Institutes of Health (HL-36235) and Merck and helpful discussions with Dr. Trevor Payne are gratefully acknowledged. Mass spectra were obtained at the UCSF resource (A.L. Burlingame, Director, NIH RR01614).

(33) (a) Strube, R. E. *Org. Synth.* **1957**, *37*, 34. (b) Eliel, E. L.; Banks, H. D. *J. Am. Chem. Soc.* **1972**, *94*, 171.

(34) Deems, R. A.; Dennis, E. A. *Methods Enzymol.* **1981**, *71*, 703.
(35) Wells, M. A. *Biochemistry* **1974**, *13*, 2248.

Communications to the Editor

Oxygenation of Polychloro Aromatic Hydrocarbons by a Superoxide Ion in Aprotic Media

Hiroshi Sugimoto, Shigenobu Matsumoto, and Donald T. Sawyer*

Department of Chemistry, Texas A&M University College Station, Texas 77843

Received September 1, 1987

Although primary and secondary haloalkanes and polychloroethenes are readily oxidized by superoxide ion ($O_2^{\bullet-}$) in aprotic media,[1,2] chlorobenzene and monohalogenated aromatic hydrocarbons do not react at significant rates.[3] This has prompted the belief that all halogenated aromatic hydrocarbons are unreactive. However, we now report that hexachlorobenzene, pentachlorobenzene, tetrachlorobenzene, and trichlorobenzene as well as decachlorobiphenyl and other "heavy" polychlorobiphenyls (PCB's) are rapidly oxygenated by $O_2^{\bullet-}$ in dimethylformamide, acetonitrile, or dimethyl sulfoxide.

The extent of the reactions for electrogenerated $O_2^{\bullet-}$ and $(Me_4N)O_2$[4] with polychloro aromatics has been determined by cyclic voltammetric assay of $O_2^{\bullet-}$ concentrations and their decrease in the presence of excess polychloroaromatic substrates. The overall reaction and product stoichiometries for the degradation of various polychloro aromatics by $O_2^{\bullet-}$ in dimethylformamide (DMF) are summarized in Table I.[5] Within the limits of a reaction time of 60 min or less, chlorobenzene and dichlorobenzenes are not oxidized. Although the trichlorobenzenes react, the rates are too slow to ascertain the stoichiometries and the products.

The reactivities of the various substrates have been determined by cyclic voltammetry via measurement of the decay rate of superoxide ion concentration,[6] and the apparent rate constants are summarized in Table I. The latter correlate with the reduction potentials for the substrates; the more positive the potential the greater the reactivity with $O_2^{\bullet-}$, which is in accord with the oxygenation of alkyl chlorohydrocarbons.[3]

Although the substrates are degraded by $O_2^{\bullet-}$ in acetonitrile and dimethyl sulfoxide, the rates of reaction are about one-tenth as great in MeCN and 20 times slower in Me_2SO. A reasonable initial step for these oxygenations is nucleophilic addition of $O_2^{\bullet-}$ to the polyhalobenzene (e.g., C_6Cl_6; Scheme I). Subsequent loss

(1) Sawyer, D. T.; Valentine, J. S. *Acc. Chem. Res.* **1981**, *14*, 393-400.
(2) Calderwood, T. S.; Neuman, R. C., Jr.; Sawyer, D. T. *J. Am. Chem. Soc.* **1983**, *105*, 3337-3339.
(3) Roberts, J. L., Jr.; Calderwood, T. S.; Sawyer, D. T. *J. Am. Chem. Soc.* **1983**, *105*, 7691-7696.
(4) (a) Sawyer, D. T.; Calderwood, T. S.; Yamaguchi, K.; Angelis, C. T. *Inorg. Chem.* **1983**, *22*, 2577-2583. (b) Yamaguchi, K.; Calderwood, T. S.; Sawyer, D. T. *Inorg. Chem.* **1986**, *25*, 1289-1290.

(5) Stoichiometries were determined by incremental titration with substrate of a known amount of $O_2^{\bullet-}$ [1-40 mM; electrosynthesized or from $(Me_4N)O_2$], with the residual $O_2^{\bullet-}$ determined by positive-scan voltammetry. The yield of Cl^- was determined by positive-scan voltammetry at ±0.95 V vs SCE (confirmed by $AgNO_3$ titration) and the yield of base (after dilution with H_2O) by titration with HCl (titration curves for the product solutions were identical with that for $C_2O_6^{2-}$ ion).[8]
(6) Nicholson, R. S.; Shain, I. *Anal. Chem.* **1964**, *36*, 706-723.

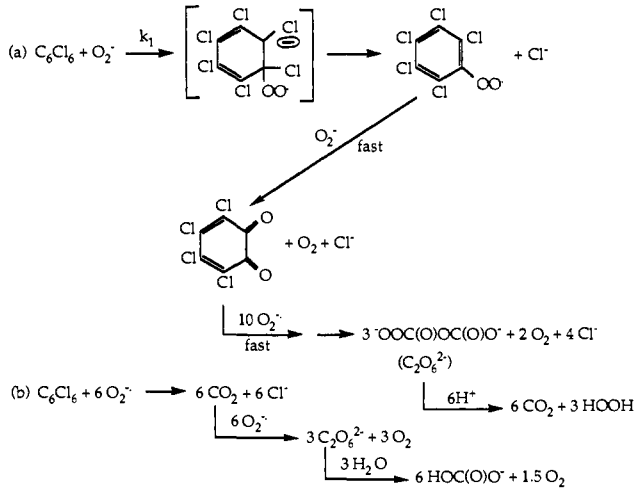
0002-7863/87/1509-8081$01.50/0

Table I. Reactions of Superoxide Ion with Polychloro Aromatics in Dimethylformamide[a]

substrates (S)	E_{pc}[b] V vs SCE	$O_2^{\bullet-}$/S	Cl^- released/S	base released/S	$k_1/[S]$,[c] M^{-1} s^{-1}
C_6Cl_6[d]	-1.48, -1.69	12.0 ± 1.0	6.0 ± 0.5	6.0 ± 0.6	1×10^3
C_6HCl_5	-1.70, -1.98	11.0 ± 1.0	5.0 ± 0.5	6.0 ± 0.6	8×10^1
1,2,3,4-$C_6H_2Cl_4$	-1.90, -2.18	10.0 ± 1.0	4.0 ± 0.5	6.0 ± 1.0	2×10^0
1,2,3,5-$C_6H_2Cl_4$	-1.95, -2.19	10.0 ± 1.0	4.0 ± 0.5	6.0 ± 1.0	1×10^0
1,2,4,5-$C_6H_2Cl_4$	-1.95, -2.19	10.0 ± 1.0	4.0 ± 0.5	6.0 ± 1.0	3×10^0
1,2,4-$C_6H_3Cl_3$	-2.16, -2.45				2×10^{-2}
$C_{12}Cl_{10}$	-1.50, -1.78	22.0 ± 4.0	10.0 ± 1.0	12.0 ± 2.0[e]	2×10^2
CCl_4[f]	-1.2	5.0 ± 0.6	4.0 ± 0.4	1.0 ± 0.1	1×10^3
$PhCCl_3$[f]	-1.47	4.0 ± 0.4	3.0 ± 0.4		4×10^1

[a] Overall reactions: (1) $C_6Cl_6 + 12O_2^{\bullet-} \rightarrow 3C_2O_6^{2-} + 6Cl^- + 3O_2$; (2) $C_6H_2Cl_4 + 10O_2^{\bullet-} \rightarrow 2C_2O_6^{2-} + 2HOC(O)O^- + 4Cl^- + O_2$; (3) $C_{12}Cl_{10} + 22O_2^{\bullet-} \rightarrow 6C_2O_6^{2-} + 10Cl^- + 4O_2$. [b] First two reduction peaks are listed; a separate peak is observed for each chlorine atom. For C_6Cl_6 the other peak potentials are -1.95, -2.18, -2.44, and -2.70 V (also the reduction potential for PhCl). [c] Apparent pseudo-first-order rate constants, k (normalized to unit substrate concentration [S]), were determined from the ratio ($i_{anodic}/i_{cathodic}$) for the cyclic voltammogram of O_2 in the presence of excess substrate, ref 6. [d] The values of $k_1/[S]$ for C_6Cl_6 in MeCN and Me_2SO solvents are 92 and 47 M^{-1} s^{-1}, respectively. [e] Titration curve indicates the presence of a weak base, and a white precipitate forms during the last part of the titration; both consistent with the presence of oxalate ion. [f] The ring-disc voltammetric technique for reaction rates gave values for $k_1/[S]$ of 3.8×10^3 M^{-1} s^{-1} for CCl_4 and 50 M^{-1} s^{-1} for $PhCCl_3$ (ref 3).

Scheme I



of chloride ion will give a benzoperoxy radical, which will be reduced by a second $O_2^{\bullet-}$ to become a peroxo nucleophile that can attack the adjacent carbochloro center with displacement of its chloride and apparent formation of an orthoquinone. The latter undergoes facile reactions with $O_2^{\bullet-}$ to give peroxy dicarbonate ($C_2O_6^{2-}$)[7,8] and chloride ions. The $C_2O_6^{2-}$ ions are hydrolyzed by water to $HOC(O)O^-$ and O_2. Thus, Scheme I outlines a possible mechanism, but the fragmentation steps are speculative and not supported by the detection of any intermediate species.

When Arochlor 1268 (a commercial PCB fraction that contains a mixture of Cl_7, Cl_8, Cl_9, and Cl_{10} polychlorobiphenyls) is combined with excess $O_2^{\bullet-}$, the entire mixture is degraded. Samples taken during the course of the reaction confirm that (a) the most heavily chlorinated members react first (the initial nucleophilic addition is the rate determining step) and (b) all components are completely dehalogenated. Tests with other PCB mixtures establish that those components with three or more chlorine atoms per phenyl ring are completely degraded by $O_2^{\bullet-}$ within several hours.

The present results also indicate that in-vivo superoxide ion may react with ingested C_6Cl_6 (a known animal carcinogen),[9] PCB's (environmental toxins that cause birth defects, organ damage, and tumors in experimental animals),[10] and other polyhalogenated hydrocarbons. The proposed peroxy radical intermediates of Scheme I are likely toxins, and their reactivity with biomembranes and lipids may represent the mechanism for the cytotoxicity of C_6Cl_6 and PCB's.

Acknowledgment. This work was supported by the National Science Foundation under Grant no. CHE-8516247 and the Welch Foundation under Grant no. A-1042.

(7) Benzyl (an α-dicarbonyl) undergoes nucleophilic addition and oxidative cleavage by $O_2^{\bullet-}$ to give two benzoate ions; Sawyer, D. T.; Stamp, J. J.; Menton, K. A. *J. Org. Chem.* **1983**, 48, 3733-3736. *o*-Tetrachloroquinone undergoes rapid and complete degradation by 10 $O_2^{\bullet-}$ ions to $3C_2O_6^{2-}$ and $4Cl^-$ ions.

(8) Superoxide ion reacts with CO_2 to give peroxy dicarbonate ($C_2O_6^{2-}$), which hydrolytically decomposes to $HOC(O)O^-$ and O_2: Roberts, J. L., Jr.; Sawyer, D. T. *J. Am. Chem. Soc.* **1984**, *106*, 4667-4670.

(9) Takazaura, R. S.; Strobel, H. W. *Biochemistry* **1986**, *25*, 4804-4809.

(10) Safe, S. *CRC Critical Rev. Tox.* **1984**, *13*, 319-396.

Oxidation of *tert*-Butyl Alcohol to Isobutylene Oxide: Rate-Limiting C-H Activation by a Ag(110) Surface

Robert L. Brainard and Robert J. Madix*

Department of Chemical Engineering
Stanford University, Stanford, California 94305
Received April 9, 1987

The oxidation of primary and secondary alcohols on Ag(110)[1,2] and Cu(110)[2-5] surfaces under ultrahigh vacuum conditions (UHV) is now fairly well understood. Generally, the first step involves the reaction of an adsorbed alcohol molecule with surface oxygen to form a surface bound alkoxide and water. Upon further heating the surface alkoxide reacts and yields an aldehyde (or ketone) and $H_{(a)}$, presumably by reaction of the hydrogen α to oxygen with the surface. Recombination reactions produce the parent alcohol, water, and/or H_2.

We report here the reaction of *tert*-butyl alcohol on preoxygenated Ag(110) surfaces. This is the first study of the reaction of a tertiary alcohol with a metal surface, although the homogeneous chemistry of tertiary metal alkoxides has been studied extensively.[6] Indeed, this alcohol exhibits much different surface chemistry than do primary and secondary alcohols. *tert*-Butyl alcohol reacts on oxygen-covered silver below 200 K yielding *t*-$BuO_{(a)}$ and water.[7] At higher temperatures (420-600 K), *t*-$BuO_{(a)}$ reacts to yield isobutylene oxide (rel yield 100%), *tert*-butyl alcohol (50%), water (45%), isobutylene (50%), acetone (20%), and CO_2 (8%). No H_2 or CO were produced. *t*-$BuO_{(a)}$ is stable to temperatures 160-250 K higher than primary and secondary alkoxides on this surface.[1,2]

The surface of a Ag(110) crystal at 120 K covered with 0.25 mL of $O_{(a)}$ was dosed with 2 L of $(CH_3)_3COD$ and heated to 700

(1) Wachs, I. E.; Madix, R. J. *Surf. Sci.* **1978**, *76*, 531-558.
(2) Wachs, I. E.; Madix, R. J. *Appl. Surf. Sci.* **1978**, *1*, 303-328.
(3) Wachs, I. E.; Madix, R. J. *J. Catal.* **1978**, *53*, 208-227.
(4) Bowker, M.; Madix, R. J. *Surf. Sci.* **1980**, *95*, 190-206.
(5) Bowker, M.; Madix, R. J. *Surf. Sci.* **1982**, *116*, 549-572.
(6) Schrock, R. R. *J. Organomet. Chem.* **1986**, *300*, 249-262. Weingrovius, J. H.; Schrock, R. R. *Organometallics* **1982**, *1*, 148. Listemann, M. L.; Schrock, R. R. *Organometallics* **1985**, *4*, 74. Schrock, R. R.; Listemann, M. L.; Sturgeoff, L. G. *J. Am. Chem. Soc.* **1982**, *104*, 4291. Chisholm, M. H.; Hoffman, D. M.; Huffman, J. C. *Organometallics* **1985**, *4*, 986-993. Chisholm, M. H.; Reichhert, W. W.; Cotton, F. A.; Murillo, C. A. *J. Am. Chem. Soc.* **1977**, *99*, 1652-1654. Bradly, D. C.; Mehrotra, R. C.; Gaur, D. P. *Metal Alkoxides*; Academic Press: New York, 1978.
(7) *tert*-Butyl alcohol does not react with the clean Ag(110) surface.

0002-7863/87/1509-8082$01.50/0