L. Cochran, F. J. Adrian, and V. A. Bowers, *ibid.*, **40**, 213 (1964); P. H. Kasai and E. B. Whipple, *J. Am. Chem. Soc.*, **89**, 1033 (1967).
(10) G. M. Whitesides, C. P. Casey, and J. K. Krieger, *J. Am. Chem. Soc.*, **93**, 1379 (1971). This paper details the arguments on which the use of vinylic stereochemistry to test for free-radical intermediates results.
(11) For reviews and recent applications of enolates in synthesis, see H. O. House, "Modern Synthetic Reactions", W. A. Benjamin, Menlo Park, Calif., 1972, Chapter 9; H. O. House, *Rec. Chem. Prog.*, **28**, 99 (1967); G. Stork and P. F. Hudrlik, *J. Am. Chem. Soc.*, **90**, 4462, 4464 (1968); H. O. House, L. J. Czuba, M. Gall, and H. D. Olmstead, *J. Org. Chem.*, **34**, 2324 (1969); I. J. Borowitz, E. W. R. Casper, R. K. Crouch, and K. C. Yee, *ibid.*, **37**, 3873 (1972); H. O. House and V. Kramer, *J. Org. Chem.*, **28**, 3362 (1963); H. O. House and B. M. Trost, *ibid.*, **30**, 1341, 2502 (1965); H. O. House, R. W. Giese, K. Kronberger, J. P. Kaplan, and J. F. Simeone, *J. Am. Chem. Soc.*, **92**, 2800 (1970); S. D. Darling, O. N. Devgan, and R. E. Cosgrove, *ibid.*, **92**, 696 (1970); R. B. Bates, L. M. Kroposki, and D. E. Potter, *J. Org. Chem.*, **37**, 560 (1972).
(12) D. Seyferth and L. G. Vaughan, *J. Am. Chem. Soc.*, **86**, 883 (1964).
(13) E. J. Panek, B. L. Neff, H. Chu, and M. G. Panek, *J. Am. Chem. Soc.*, **97**, 3996 (1975).
(14) Reaction of sodium *m*-chloroperbenzoate with (*Z*)-**2** in THF at temperatures from −78 to 0 °C generated only low (~20%) yields of enolates.
(15) J. E. Bennett and J. A. Howard, *Chem. Phys. Lett.*, **9**, 460 (1971).
(16) P. West and R. Waack, *J. Am. Chem. Soc.*, **89**, 4392 (1967).
(17) See C. Walling and A. Padwa, *J. Am. Chem. Soc.*, **85**, 1593 (1963); S. F. Nelson and P. D. Bartlett, *ibid.*, **88**, 137 (1966).
(18) H. R. Ward, *Acc. Chem. Res.*, **5**, 18 (1972).
(19) G. M. Whitesides, E. J. Panek, and E. R. Stedronsky, *J. Am. Chem. Soc.*, **94**, 232 (1972).
(20) P. Warner and S.-L. Lu, *J. Org. Chem.*, **41**, 1459 (1976).
(21) H. C. Brown et al., "Organic Synthesis via Boranes", Wiley, New York, N.Y., 1975; G. Linstrumelle, J. K. Krieger, and G. M. Whitesides, *Org. Synth.*, **53**, 165 (1975).
(22) E. J. Panek and W. F. Carroll, Jr., *J. Org. Chem.*, submitted.
(23) D. J. Foster and E. Tobler, *J. Org. Chem.*, **27**, 834 (1962); D. Y. Curtin and M. J. Hurwitz, *J. Am. Chem. Soc.*, **74**, 5381 (1952).
(24) R. Ramirez and S. Dershowitz, *J. Org. Chem.*, **22**, 41 (1957).
(25) H. O. House, W. L. Respess, and G. M. Whitesides, *J. Org. Chem.*, **31**, 3128 (1966).
(26) K. Noack and R. N. Jones, *Can. J. Chem.*, **39**, 2225 (1961); H. O. House, D. D. Traficante, and R. A. Evans, *J. Org. Chem.*, **28**, 348 (1963).
(27) R. C. Fahey and D. C. Lee, *J. Am. Chem. Soc.*, **88**, 5555 (1966).
(28) S. W. Tobey, *J. Org. Chem.*, **34**, 1281 (1969).
(29) J. D'Ans and H. Gold, *Chem. Ber.*, **92**, 2559 (1959).

---

# Spin Trapping, Alkylperoxy Radicals, and Superoxide–Alkyl Halide Reactions

**Margaret V. Merritt***[1a] **and Roy A. Johnson**[1b]

*Contribution from Physical and Analytical Chemistry Research and Experimental Chemistry Research, The Upjohn Company, Kalamazoo, Michigan 49001.* *Received November 11, 1976*

**Abstract:** Spin trapping has been used to study the reaction of dicyclohexyl-18-crown-6 solubilized potassium superoxide with alkyl halides and alkyl sulfonate esters. Alkoxy radicals, rather than the initial alkylperoxy radical products, were detected with *N-tert*-butyl-$\alpha$-phenylnitrone (PBN). Alkylperoxy radical adducts of PBN were formed only at low temperatures; the spectral parameters of these adducts are reported.

The technique of spin trapping has been developed to detect and identify radicals too short lived for direct ESR observation.[2a] In this approach, a transient radical reacts with a spin trap to produce a persistent[2b] radical, a spin adduct. The ESR spectrum of the adduct is characteristic of the trapped radical and can aid in identifying the transient species. Spin trapping of alkylperoxy radicals has not been previously reported. These radicals have been shown to be the initial products from reaction of alkyl halides or alkyl sulfonate estersizith superoxide in dimethyl sulfoxide ($Me_2SO$),[3,4] *N*,*N*-dimethylformamide (DMF), acetonitrile,[5] and benzene.[6] We have selected this reaction as a convenient source of alkylperoxy radicals from readily available starting materials for spin trapping studies in a variety of solvents. We report here on the trapping of *alkoxy* radicals with *N-tert*-butyl-$\alpha$-phenylnitrone (PBN) in this reaction as well as on conditions under which alkylperoxy adducts of PBN were observed. Mechanistic implications of these results are discussed.

## Experimental Section

All ESR measurements were made on a Varian E-9 ESR spectrometer using an E-232 dual sample cavity with a variable temperature insert. Temperature regulation was achieved with a Varian E-257 variable temperature controller. Measurements of *g* values were made relative to $\alpha,\alpha$-diphenyl-$\beta$-picrylhydrazyl (DPPH) (Aldrich), $g = 2.0037 \pm 0.0002$.[7] Absolute spin concentrations were determined relative to standard solutions of 4-hydroxy-2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPOL) (Aldrich). Double integration of the first derivative spectra was accomplished with a Nicolet 1020 signal averager.

**Chemicals.** All solvents were Burdick and Jackson distilled in glass. Lead tetraacetate (Matheson Coleman and Bell), potassium superoxide (Ventron), and PBN (Aldrich) were used as received. Dicyclohexyl-18-crown-6 (Du Pont) was a mixture of stereoisomers and was used without purification. 5,5′-Dimethyl-1-pyrroline 1-oxide (DMPO) was prepared as described by Iwamura and Inamota[8] from a detailed procedure by Chen.[9] Di-*n*-octyl peroxide was synthesized from *n*-octyl bromide by reaction with $KO_2$ in benzene.[6] *n*-Octadecyl mesylate and 2-octyl tosylate were made from the corresponding alcohols by conventional reactions. *n*-Pentyl hydroperoxide and *sec*-butyl hydroperoxide were synthesized by hydrogen peroxide oxidation of *n*-pentyl and *sec*-butyl methyl sulfonate esters, respectively.[10] Cumene and *tert*-butyl hydroperoxides were obtained from K & K Laboratory. These four hydroperoxides were purified just prior to use by procedures similar to those described by Bartlett.[11] Compounds not mentioned were obtained from commercial sources and used without purification.

***n*-Octadecyl Hydroperoxide.** A mixture of potassium superoxide (1.17 g, 16.5 mmol) in dry dimethyl sulfoxide (30 mL) containing dicyclohexyl-18-crown-6 (0.614 g, 1.65 mmol) was prepared and stirred at room temperature. *n*-Octadecyl tosylate (2.12 g, 5 mmol) was added as a solid. Considerable foaming was observed after the addition. After 90 min, the reaction mixture was worked up by careful addition of brine (100 mL) followed by extraction with methylene chloride (four times). The organic extract was dried ($Na_2SO_4$), filtered, concentrated, and chromatographed on a column of silica gel (150 g) packed as a slurry in benzene. Elution was with benzene (44 fractions) and 20% ethyl acetate-benzene (10 fractions). Fractions of 100-mL volume were collected. Fractions 2 and 3 contained di-*n*-octadecyl peroxide (0.091 g, 0.169 mmol, 7%), fraction 4 contained starting material (0.036 g), fractions 5-13 contained *n*-octadecyl hydroperoxide, mp 54-56 °C, lit.[12] mp 49-50 °C (0.509 g, 1.78 mmol, 35%), and fractions 16-47 contained 1-octadecanol (0.601 g, 2.23 mmol, 44%).

**ESR Sample Preparation. Crown Solubilized-$KO_2$ Reaction with Organic Substrates in the Presence of PBN.** Ca. 3-5 mg of $KO_2$ ($5 \times 10^{-5}$ mol), 2.0 mL of a stock solution of dicyclohexyl-18-crown-6

**Table I.** Mean ESR Spectral Parameters of PBN Spin Adducts in Reaction of RX with Dicyclohexyl-18-crown-6 Solubilized $KO_2$ in Various Solvents

| | $a_N$[a] | | $a_H$[a] | | $g$ | |
|---|---|---|---|---|---|---|
| Solvent | *b* | *c* | *b* | *c* | *b* | *c* |
| | | | Primary RX | | | |
| $CH_3CN$ | 13.83 ± 0.01 | 13.87 | 2.27 ± 0.01 | 2.24 | 2.0063 | 2.0062 |
| DMF | 13.77 ± 0.01 | 13.77 | 2.26 ± 0.01 | 2.26 | 2.0063 | 2.0062 |
| $Me_2SO$ | 13.83 ± 0.01 | 13.84 | 2.26 ± 0.01 | 2.26 | 2.0063 | 2.0062 |
| THF | 13.61 ± 0.01 | 13.61 | 2.03 ± 0.01 | 1.98 | 2.0063 | 2.0063 |
| Benzene | 13.64 ± 0.04 | | 1.94 ± 0.02 | | 2.0063 | |
| $CH_2Cl_2$ | | 13.85 ± 0.09 | | 2.19 ± 0.04 | | 2.0062 |
| | | | Secondary RX | | | |
| $CH_3CN$ | 13.89 ± 0.06 | 13.92 | 1.96 ± 0.08 | 1.96 | 2.0063 | 2.0062 |
| DMF | 13.83 ± 0.08 | 13.82 | 2.03 ± 0.08 | 1.93 | 2.0062 | 2.0062 |
| $Me_2SO$ | 13.89 ± 0.01 | 13.89 | 2.05 ± 0.08 | 1.94 | 2.0062 | 2.0062 |
| THF | 13.68 ± 0.12 | 13.64 | 1.88 ± 0.04 | 1.73 | 2.0063 | 2.0063 |
| Benzene | 13.74 ± 0.06 | | 1.77 ± 0.04 | | 2.0063 | |
| $CH_2Cl_2$ | | 13.83 ± 0.01 | | 1.89 ± 0.07 | | 2.0063 |

[a] Coupling constants in gauss; precision is expressed as the standard deviation. [b] Mean values from direct reaction of RX with dicyclohexyl-18-crown-6 solubilized $KO_2$. [c] Values measured for the spin adduct originally formed in benzene from 1-bromopentane (primary RX) or 2-bromopentane (secondary RX) with dicyclohexyl-18-crown-6 solubilized $KO_2$ in presence of PBN. The benzene was replaced by vacuum distillation by the solvent indicated and the ESR spectrum recorded.

(0.025 M) and PBN (0.05 M), and ca. $5 \times 10^{-5}$ mol of the organic substrate were sealed in a 15-mL centrifuge tube. After shaking for at least 4 h on a Burrell wrist-action shaker, the tube was centrifuged to remove any excess $KO_2$ and solid product. An aliquot of the supernatant was transferred to a Pyrex cyclindrical ESR cell, vacuum degassed, and the ESR spectrum recorded. Several control samples were prepared in which one of the reagents per sample was omitted for each solvent used. 1-Bromopentane was the organic substrate in these controls. Samples in which DMPO was used as the spin trap were prepared and examined in identical fashion. The following compounds were the organic substrates used in preparation of the ESR samples in benzene: bromoethane, 1-bromopropane, 2-bromopropane, 1-chloropropane, 2-chloropropane, 3-bromo-1-propane, 1-bromobutane, 1-bromo-3-methylpropane, 1-bromo-2-methylbutane, 1-bromopentane, 1-bromohexane, bromomethylcyclohexane, methyl 6-bromohexanoate, 5-bromo-1-pentene, 6-bromo-1-hexene, benzyl bromide, 1-bromooctadecane, *n*-octadecyl mesylate, cyclopentyl bromide, cyclohexyl bromide, 2-bromooctane, 2-bromopentane, 2-bromoheptane, 2-bromoundecane, 2-bromododecane, 2-bromo-3-phenylpropane, and 2-octyl tosylate. A smaller number of the same substrates was used to prepare ESR samples for study of the $KO_2$–RX reaction in the presence of PBN in acetonitrile, DMF, $Me_2SO$, and THF.

The following experiment was designed to determine the stability of the PBN spin adducts to the $KO_2$–RX reaction conditions. A 2.00-mL aliquot of a benzene stock solution of dicyclohexyl-18-crown-6 (0.025 M) and 1-bromopentane (0.025 M) was transferred to a centrifuge tube containing 5–6 mg of $KO_2$ and 102 mg of PBN. The tube was shaken for 16 h and an aliquot taken for ESR measurement. A 1.00-mL portion was transferred to a second centrifuge tube containing 1.00 mL of the stock solution, 101 mg of PBN, and 5 mg of $KO_2$. This second sample was shaken for 16 h prior to taking an aliquot for ESR examination. The relative concentrations of the spin adduct in the two samples were determined by double integration of the first derivative spectra.

A series of benzene samples were prepared in which the concentration of $KO_2$, 1-bromopentane, and dicyclohexyl-18-crown-6 were 0.16 M and that of PBN varied from 0.008 to 1.41 M. To ensure completeness of reaction, the samples were shaken for 48 h prior to taking aliquots for ESR examination. In this case, the relative concentrations of spin adduct were determined from the height of the $M = 0$ line normalized with respect to the spectral height of a standard of DPPH contained in the second channel of the dual sample cavity. Absolute spin concentration measurements were made at PBN concentrations greater than 0.3 M for this reaction in both benzene and $Me_2SO$. Similarly a set of samples was prepared and examined by ESR in which the concentrations of PBN, dicyclohexyl-18-crown-6, and 1-bromopentane were fixed and the $KO_2$ varied from a $KO_2$/1-bromopentane molar ratio of 0.5 to 5.0. Spectra of the spin adducts were obtained from samples in $Me_2SO$ in which the concentration of $KO_2$, 18-crown-6, and 1-bromohexane matched those of San Filippo et al.[4]

**Solvent Exchange.** Aliquots from the reaction of 1-bromopentane and 2-bromopentane run on a large scale in benzene were transferred to ESR cells and the benzene removed by vacuum distillation. A second solvent was distilled into each cell, the contents mixed, and the ESR spectra recorded.

**Reaction of Lead Tetraacetate with Alkyl Hydroperoxides.** Alkylperoxy radicals were generated in a two-compartment ESR cell as follows. An aliquot of hexane solution of freshly purified alkyl hydroperoxide was deposited in the 3-mm Pyrex stem of the cell. Removal of the hexane with a stream of nitrogen left ca. 5 mg of alkyl hydroperoxide evenly coating the walls. Following addition of 0.5 mL of $Pb(OAc)_4$ solution (3 mg/mL in methylene chloride or a saturated benzene solution) to the side arm, the cell was vacuum degassed without mixing the contents of the two chambers. In some cases, 20 mg of PBN (or DMPO) was also added to the side arm prior to degassing. For low temperature alkylperoxy radical generation, the contents were mixed in a dry ice/acetone bath and the ESR spectrum recorded at −80 °C. For room temperature generation, the contents were mixed and the spectrum recorded at ambient temperature. In some cases, the original solvent was replaced with another by vacuum distillation and a second ESR spectrum recorded. Control samples containing (a) $Pb(OAc)_4$ and PBN, (b) PBN and the alkyl hydroperoxides in both solvents, and (c) 1-pentanol or 1-octanol, $Pb(OAc)_4$, and PBN were prepared under identical conditions and their ESR spectra recorded.

## Results

Table I contains the mean ESR spectral parameters of the PBN adducts formed from reaction of alkyl halides and sulfonate esters with dicyclohexyl-18-crown-6 solubilized $KO_2$ in the presence of PBN. With few exceptions, only one nitroxide was observed in each spectrum. Evidence of an additional nitroxide was noted from the following substrates: *n*-propyl chloride, isopropyl chloride, cyclopentyl, 2-undecyl, and 2-dodecyl bromides. In these cases, the amplitude of an additional line on the high-field line of the major nitroxide was estimated to be no more than 10% of the major component. The results of the solvent exchange experiments are also contained in Table I.

No radicals were detected by ESR from the following controls in each solvent: (a) PBN, 1-bromopentane, and dicyclo-

Table II. Concentration of PBN Spin Adducts Formed from Known RX-$KO_2$ Reaction Products and Dicyclohexyl-18-crown-6 Solubilized $KO_2$ in Benzene and $Me_2SO$ in the Presence of PBN Relative to That from Corresponding RBr

| Product | Solvent | $\frac{[\text{Adduct}]}{[\text{R-Br-adduct}]}$ | Obsd radical |
|---|---|---|---|
| 1-$C_8H_{17}OH$ | Benzene | 0.03 | *a* |
| | $Me_2SO$ | 0.03 | *a* |
| $C_7H_{15}C(=O)H$ | Benzene | 0.02 | *a* |
| | $Me_2SO$ | 0.03 | *a* |
| [1-$C_8H_{17}O]_2$ | Benzene | 0.01 | *a* |
| | $Me_2SO$ | <0.01 | *a* |
| $C_5H_{11}O_2H$ | Benzene | ~1 | *b* |
| | $Me_2SO$ | 0 | |
| $C_{18}H_{37}O_2H$ | Benzene | ~1 | *b* |
| | $Me_2SO$ | 0 | |

[a] Coupling constants and *g* value of observed radicals differ from those from RBr reaction. [b] Coupling constants and *g* value of observed radical identical with those from RBr reaction.

hexyl-18-crown-6, (b) PBN, $KO_2$, and dicyclohexyl-18-crown-6, and (c) 1-bromopentane, $KO_2$, and dicyclohexyl-18-crown-6. The absence of nitroxides indicated that the observed spin adducts arise from a product of the alkyl bromide-$KO_2$ reaction and not from reaction of one of the starting materials and PBN. The sample containing 1-bromopentane, $KO_2$, and PBN produced the same nitroxide as seen in the presence of crown ether, although at a much lower concentration. This observation is in accord with that of Johnson and Nidy that the $KO_2$-alkyl bromide reaction with $KO_2$ proceeded slowly in benzene in the absence of crown ether.[6] The use of either 18-crown-6 or dibenzo-18-crown-6 as the solubilizing agent in this reaction with 1-bromohexane as the substrate yielded the same nitroxide as with the dicyclohexyl-18-crown-6.

Observation of radicals from samples containing only DMPO and $KO_2$ and dicyclohexyl-18-crown-6 suggested that DMPO and $KO_2$ react directly. No further studies with DMPO were pursued.

Experiments were performed in which known products of the alkyl halide-$KO_2$ reactions were equilibrated with dicyclohexyl-18-crown-6, $KO_2$, and PBN in both benzene and $Me_2SO$ under conditions identical with that of a reference sample of the corresponding alkyl bromide. The ESR spectra of these samples were recorded and integrated. The results of these experiments are contained in Table II. Only the alkyl hydroperoxides in benzene yielded significant amounts of a nitroxide with coupling constants and a *g* value identical with that formed from the alkyl bromide.

The use of nitrones as spin traps is complicated by the ease with which they react with some anions to yield aminooxy anions, air oxidizable to nitroxides.[13] Consequently, ESR samples were prepared in which $K_2CO_3$, KBr, or KOH was substituted for $KO_2$ and compared to a reference sample of $KO_2$, dicyclohexyl-18-crown-6, 1-bromopentane, and PBN in benzene and $Me_2SO$. Similar experiments were performed in which 1-pentyl hydroperoxide was substituted for 1-bromopentane. The spectral properties of any detectable radicals differed from those of the reference and their concentrations did not exceed ca. 2% of the reference. Consequently, we concluded that neither the inorganic anion products of this reaction nor the peroxide anion was responsible for the observed nitroxides.

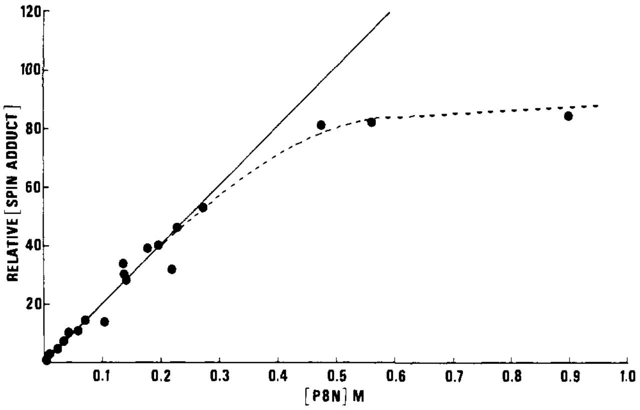


Figure 1. The relative concentration of the PBN spin adduct formed as a function of PBN concentration from reaction of 1-bromopentane with dicyclohexyl-18-crown-6 solubilized $KO_2$ in benzene.

Figure 1 contains the plot of the relative concentration of the PBN spin adduct formed in the 1-bromopentane-$KO_2$ reaction in benzene as a function of PBN concentration. A least-squares fit of these data for 0.008 M ≤ [PBN] ≤ 0.3 M yielded a straight line with unity slope; the correlation coefficient was 0.965. The observed coupling constants were invariant with respect to PBN concentration. Absolute spin concentration measurements of these samples and similar ones in both benzene and $Me_2SO$ at [PBN] > 0.5 M revealed that ca. 1% of the maximum possible number of radicals were trapped based on starting alkyl bromide.

In the experiment in which a benzene solution of the PBN adduct from 1-bromopentane was the solvent for a second reaction of this substrate, the final concentration of the spin adduct was the sum of that from the initial solution and that predicted by the data in Figure 1 for the second reaction. This result was interpreted to mean that the spin adducts were not destroyed by the $KO_2$-alkyl bromide reaction conditions.

The identity of the spin adduct formed in $Me_2SO$ was not altered by (a) the ratio of $KO_2$/1-bromopentane, nor (b) the particular crown ether used as evidenced by the invariance of *g* values and coupling constants with alterations in this ratio and with substitution of other crowns for dicyclohexyl-18-crown-6.

Single line ESR spectra were observed from the reaction of $Pb(OAc)_4$ at −80 °C with the alkyl hydroperoxides (ROOH)[14] except for the *n*-octadecyl compound. The *g* values of the spectra, ranging from 2.011 to 2.015, are characteristic of alkylperoxy radicals.[15] The single line spectra were replaced by ones characteristic of nitroxides on addition of PBN to the samples. In the presence of PBN, the $Pb(OAc)_4$-ROOH reaction at −80 °C yielded only these same nitroxides for all ROOH. The spectral parameters of these nitroxides, assumed to be alkylperoxy adducts of PBN, are compiled in Table III together with similar data for the nitroxides observed in the room temperature $Pb(OAc)_4$-ROOH reaction. The low solubility of *n*-octadecyl hydroperoxide in methylene chloride may account for our inability to detect the corresponding peroxy radical directly at low temperature. Control samples containing (a) $Pb(OAc)_4$ solution and PBN and (b) PBN and the alkyl hydroperoxides in both methylene chloride and benzene were examined by ESR at room temperature and −80 °C. The concentration of any nitroxide detected was less than ca. 1% of that seen with PBN, alkyl hydroperoxide, and $Pb(OAc)_4$ all present.

The following data indicated that alkylperoxy radicals generated at room temperature were not trapped by PBN. The $Pb(OAc)_4$-ROOH reaction at room temperature in benzene in the presence of PBN yielded nitroxides with spectral parameters identical with those from the reaction of crown-solubilized $KO_2$ with alkyl halides ($KO_2$-RX). After replacement of benzene with methylene chloride, the ESR spectra of these adducts were recorded at −80 °C. The observed coupling

**Table III.** ESR Spectral Data of PBN Spin Adducts formed by Generation of Alkyperoxy Radicals in the Presence of PBN

| Reaction condition | Starting material | PBN trapped radical | Temp, °C ESR | $a_N$[a] | $a_H$[a] | $g$ |
|---|---|---|---|---|---|---|
| $Pb(OAc)_4$ + ROOH in $CH_2Cl_2$ at −80°C | *t*-$BuO_2H$ | $RO_2\cdot$ | −80 | 13.39 ± 0.07 | 1.19 ± 0.05 | 2.0062 |
| | *sec*-$BuO_2H$ | $RO_2\cdot$ | −80 | 13.50 ± 0.05 | 1.40 ± 0.05 | 2.0062 |
| | *n*-$C_5H_{11}O_2H$ | $RO_2\cdot$ | −80 | 13.44 ± 0.01 | 1.39 ± 0.06 | 2.0062 |
| | $C_6H_5CMe_2$-$O_2H$[b] | $RO_2\cdot$ | −80 | 13.46 | 1.47 | 2.0062 |
| | $C_{18}H_{37}O_2H$ | $RO_2\cdot$ | −80 | 13.50 ± 0.04 | 1.17 ± 0.04 | 2.0062 |
| | | | RT | 13.50 ± 0.01 | 1.61 ± 0.04 | 2.0062 |
| $Pb(OAc)_4$ + ROOH in benzene at RT[c] | *t*-$BuO_2H$ | Mixture | | | | |
| | *sec*-$BuO_2H$ | sec-$BuO\cdot$ | RT | 13.94 | 1.91 | 2.0062 |
| | | | −80 | 13.91 | 1.83 | 2.0062 |
| | *n*-$C_5H_{11}O_2H$ | *n*-$C_5H_{11}O\cdot$ | RT | 13.89 | 2.21 | 2.0062 |
| | | | −80 | 13.91 | 2.24 | 2.0062 |
| | *n*-$C_{18}H_{37}O_2H$ | | RT | 13.86 | 2.18 | 2.0062 |
| | | Mixture | −80 | | | |

[a] Coupling constants in gauss in $CH_2Cl_2$; precision is expressed as the standard deviation. [b] One experiment only. [c] The benzene was replaced with methylene chloride by vacuum distillation. The reported spectral parameters are those of the adducts in methylene chloride; the values are the average of two separate experiments.

constants did not correspond to those of the alkylperoxy adducts (Table III). We assigned the structure of the nitroxides formed in both the $KO_2$–RX and the $Pb(OAc)_4$–ROOH reactions at room temperature to that of the alkoxy-PBN spin adduct (see Discussion section).

In the spectra from all samples of the alkylperoxy-PBN adducts generated at low temperature, except from *n*-octadecyl hydroperoxide, a second nitroxide was observed whose concentration irreversibly increased as the temperature was raised from approximately −40 °C to room temperature. The room temperature coupling constants of the second nitroxide were those of the alkoxy-PBN adducts.[16] The change in the concentration of all spin adducts as a function of temperature varied with the starting alkyl hydroperoxide and suggested a difference in stabilities among the alkylperoxy-PBN adducts. A large decrease (ca. 100 times) in the concentration of radicals observed at room temperature indicated that both the *tert*-butylperoxy- and *sec*-butylperoxy-PBN adducts decomposed to give nonradical products. On the other hand, similar measurements suggested that the adduct from *n*-pentyl hydroperoxide was thermally stable. At room temperature, the spectra of samples from the low temperature reaction of $Pb(OAc)_4$ with *n*-pentyl hydroperoxide could be interpreted to result from approximately equal concentrations of the peroxy and alkoxy PBN adducts. The peroxy adduct formed from *n*-octadecyl hydroperoxide and $Pb(OAc)_4$ at −80 °C was unique in that the alkoxy adduct was not observed on warming; furthermore, the peroxy adduct was stable at room temperature as evidenced by the constant spectral amplitude and reversibility of the temperature effects. Consequently, we suggest that the room temperature coupling constants and $g$ values for the samples in which the *n*-octadecyl peroxy radical were generated at −80 °C do represent these of *n*-$C_{18}H_{37}OO$–PBN.

No large significance should be attached to the differences in coupling constants between the adducts formed from the various alkylperoxy radicals at −80 °C. The measured values of the hydrogen coupling constants may be too high because of contamination from alkoxy-PBN adducts, particularly in the samples from *n*-pentyl and *sec*-butyl hydroperoxides. Initially it seemed possible that the alkoxy adducts might have been formed directly by reaction from $Pb(OAc)_4$ with the alcohol products formed from the hydroperoxides.[16] The formation of these materials was minimized, although not eliminated, by using a deficit of $Pb(OAc)_4$. Samples in which 1-pentanol was substituted for the hydroperoxide yielded only ca. 2% of the nitroxide concentration relative to that from the $Pb(OAc)_4$–ROOH reactions. Consequently we concluded that the reaction of $Pb(OAc)_4$ with alcoholic products was only a minor source of the trapped alkoxy radicals.

Attempts to observe alkylperoxy adducts of DMPO were unsuccessful. The results suggested that these adducts, if formed, were unstable even at −80 °C.

## Discussion

Several groups have recently reported a diverse array of products from reaction of crown ether solubilized $KO_2$ with alkyl halides and alkyl sulfonate esters. Using excess $KO_2$ in $Me_2SO$, San Filippo, Chern, and Valentine observed alcohols as the major product and aldehydes (or ketones) as minor products.[4] Corey has also reported the synthesis of alcohols via this reaction under similar aprotic conditions.[17] In contrast, Johnson and Nidy synthesized dialkyl peroxides from equimolar amounts of alkyl bromides or alkyl sulfonate esters and crown solubilized $KO_2$ in benzene; they found alcohols as minor products.[6] Both San Filippo and Johnson concluded, from the stereochemical course of the reaction, that its initial step is the nucleophilic displacement of halide by superoxide to yield an alkylperoxy radical. This mechanistic conclusion had been made previously via electrochemical studies of this reaction and a similar array of products observed: hydroperoxide,[3] dialkyl peroxides, alcohols, and aldehydes and ketones.[5] These reports all suggest that the fate of the initially formed alkylperoxy radical is quite sensitive to the reaction conditions.

The purpose of the present study was twofold: (1) to determine the capability of the common spin traps in detecting and identifying alkylperoxy radicals generated in the $KO_2$–rx reaction and (2) to use the spin trapping data to elucidate the reaction mechanism (or mechanisms) leading to such a diversity of products.

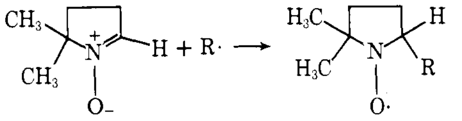
Two of the most widely used spin traps are DMPO and PBN; both react with free radicals to yield nitroxides as shown in eq 1 and 2.

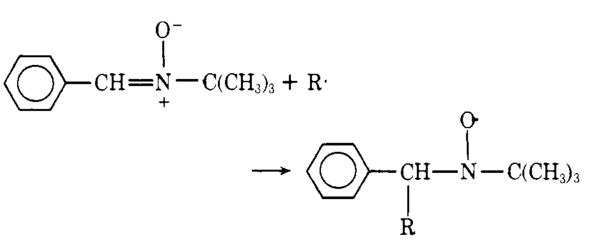
The apparent reactivity of DMPO with superoxide and the instability of the adducts from the $Pb(OAc)_4$–ROOH reaction made this trap unusable here. In contrast, our data indicated that PBN was unreactive with respect to the reagents of both

**Table IV.** ESR Spectral Parameters of Known Spin Adducts of PBN

| Trapped radical | Radical source | Solvent | $a_N$ G | $a_H$, G | $g$ |
|---|---|---|---|---|---|
| HOO·[a] | $H_2O_2 + h\nu$ | Water | 14.8 | 2.75 | 2.0057 |
| HO·[a] | $H_2O_2 + h\nu$ | Water | 15.3 | 2.75 | 2.0057 |
| HO·[b] | $H_2O$ + microwave | Benzene | 14.66 | 2.88 | |
| $CH_3$·[c] | Acetone + $h\nu$ | Benzene | 14.81 | 3.47 | |
| $CH_3CH_2$·[c] | 3-Pentanone + $h\nu$ | Benzene | 14.32 | 3.22 | |
| $n$-$C_4H_9$·[d] | $(n\text{-}C_4H_9)_4Pb + h\nu$ | Benzene | 14.64 | 3.21 | |
| $CH_3O$·[d] | $CH_3OH + Pb(OAc)_4$ | Benzene | 13.76 | 2.00 | |
| $CH_3CH_2O$·[d] | $CH_3CH_2OH + Pb(OAc)_4$ | Benzene | 14.01 | 2.01 | |
| *n*-BuO·[d] | *n*-BuOH + $Pb(OAc)_4$ | Benzene | 13.82 | 2.00 | |
| *sec*-BuO·[d] | *sec*-BuOH + $Pb(OAc)_4$ | Benzene | 13.47 | 1.80 | |
| *t*-BuO·[d] | *t*-BuOH + $Pb(OAc)_4$ | Benzene | 13.79 | 2.01 | |
| *t*-BuO·[e] | Di(*tert*-butyl) peroxalate + heat | Benzene | 14.22 | 1.95 | |
| $CH_3C(=O)$·[f] | $Hg(OAc)_2 + h\nu$ | Benzene | 12.97 | 11.82 | |
| Primary RO·[g] | Primary RX + $KO_2$ | Benzene | 13.64 | 1.94 | 2.0063 |
| Secondary RO·[g] | Secondary RX + $KO_2$ | Benzene | 13.74 | 1.77 | 2.0063 |

[a] Reference 18. [b] E. G. Janzen, T. Kasai, and K. Kuwato, *Bull. Chem. Soc. Jpn.*, **46**, 2061 (1973). [c] E. G. Janzen and I. G. Lopp, *J. Phys. Chem.*, **76**, 2056 (1972). [d] Reference 15. [e] Reference 23. [f] E. G. Janzen and B. J. Blackburn, *J. Am. Chem. Soc.*, **90**, 5909 (1968). [g] This work.


(1)


(2)

the $KO_2$-RX and the $Pb(OAc)_4$-ROOH reactions and that the PBN adducts formed were persistent.

Our conclusions derived from the ESR spectra of the spin adducts formed in the crown solubilized $KO_2$-RX reaction in the presence of PBN are as follows (see Table I): (1) The same type nitroxide was formed from a wide variety of primary and secondary alkyl halide and sulfonate esters as indicated by the invariance of coupling constants and $g$ values with substrate. (2) A significant difference in the $\beta$ coupling constants between nitroxides derived from primary substrates and those from secondary ones was, however, observed. (3) The identity of the spin adduct was not a function of reaction solvent. The coupling constants of the adducts observed in a second solvent following their formation in benzene were identical, within experimental error, with those of adducts formed directly in the second solvent. Consequently, the variation in coupling constants among solvents simply reflects a solvent dependency of these parameters. (4) The identity of the spin adduct was invariant to alterations in the ratio of $KO_2$ to organic substrate, the amount and identity of crown ether used, and the PBN concentration. (5) The observed spin adducts represent a very low product yield (1–2%) with respect to starting material as determined by absolute concentration measurements at high PBN concentrations in benzene and $Me_2SO$. The unity slope of the plot shown in Figure 1, however, for [PBN] $< 0.3$ M suggests that the observed nitroxides are derived from addition of a product of the $KO_2$-RX reaction to PBN.

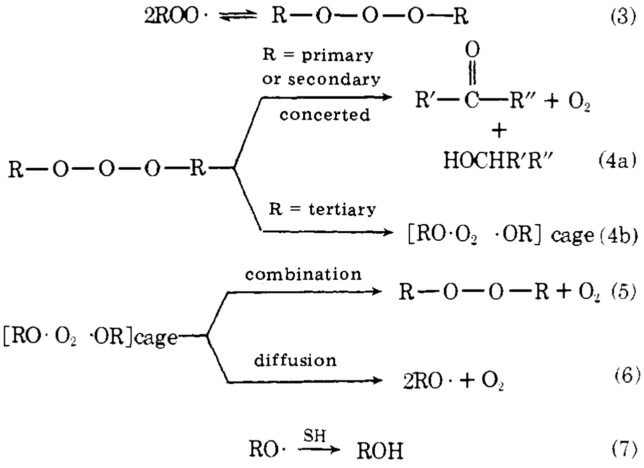
The ESR spectral properties of the adduct formed from alkylperoxy radicals generated at room temperature differed from those of the PBN adducts formed at temperatures where alkylperoxy radicals could be observed directly (Table III). These latter adducts were assumed to be those of the alkylperoxy radicals. Inspection of the coupling constants of known PBN spin adducts revealed those of alkoxy radicals to be most similar to those observed from the room temperature $KO_2$-RX and $Pb(OAc)_4$-ROOH reactions. (Table IV). Assignment of the structure of these nitroxides to alkoxy-PBN adducts and that of the adducts formed at low temperature to alkylperoxy-PBN adducts is consistent with published data on HO-PBN and $HO_2$-PBN.[18] The small difference between the coupling constants of the alkylperoxy- and alkoxy-PBN adducts at room temperature in methylene chloride and their relative sizes parallel those of the PBN derivatives of HO· and HOO· in water: 1-$C_{18}H_{37}O_2$-PBN, $a_N = 13.5$ G, $a_H = 1.6$ G, $g = 2.0062$; 1-RO-PBN, $a_N = 13.9$ G, $a_H = 2.2$ G, $g = 2.0062$; $HO_2$-PBN, $a_N = 14.8$ G, $a_H = 2.75$ G, $g = 2.0057$; HO-PBN, $a_N = 15.3$ G, $a_H = 2.75$ G, $g = 2.0057$.

Control experiments were run to determine whether alkoxy radicals were truly present in the $KO_2$-RX reactions or if our observations of alkoxy-PBN adducts were artifactual. Reaction of excess $KO_2$ with known products of the $KO_2$-RX reaction in the presence of PBN was investigated in $Me_2SO$ and benzene as possible sources of alkoxy-PBN adducts (Table II). Only alkyl hydroperoxides equilibrated with $KO_2$ and PBN and only in benzene yielded significant concentrations of a nitroxide with coupling constants matching those of the alkoxy-PBN adducts from alkyl halide substrates. Production of alkoxy radicals could not be ascribed solely to this reaction, however, since their adducts were not observed in $Me_2SO$ from $KO_2$, PBN, and alkyl hydroperoxides; alkyl hydroperoxides are known products of the $KO_2$-RX reaction in this solvent.[3,19] Further support of our assignment of the observed nitroxides as alkoxy-PBN adducts comes from Peters' and Foote's demonstration that *tert*-butoxy radicals were the major product from reaction between *tert*-butyl hydroperoxide and tetramethylammonium superoxide in acetonitrile.[20]

Our data also indicate that the nitroxide adducts were not products of decomposition of initially formed alkylperoxy-PBN adducts. The temperature dependence of the spectra of the alkylperoxy-PBN adducts formed at −80 °C revealed that only the low molecular weight adducts were thermally labile; furthermore, their decomposition yielded nonradical products. The fact that the yield of nitroxide was that predicted by simple additivity in the "twice-reacted" 1-bromopentane experiment seemed to rule out destruction of PBN adducts by reaction conditions.

The results of these control experiments lead us to the conclusion that alkoxy radicals are generated to a small, but detectable, extent from alkylperoxy radicals from either the $KO_2$-RX or $Pb(OAc)_4$-ROOH reaction at room temperature. The self-reaction of alkylperoxy radicals shown in Scheme I indicates one possible source of alkoxy radicals:[21]

**Scheme I**



$$2ROO\cdot \rightleftharpoons R{-}O{-}O{-}O{-}O{-}R \quad (3)$$

$$R{-}O{-}O{-}O{-}O{-}R \xrightarrow[\text{concerted}]{R = \text{primary or secondary}} R'{-}\overset{O}{\overset{\|}{C}}{-}R'' + O_2 + HOCHR'R'' \quad (4a)$$

$$R{-}O{-}O{-}O{-}O{-}R \xrightarrow{R = \text{tertiary}} [RO{\cdot}O_2\ {\cdot}OR]\ \text{cage} \quad (4b)$$

$$[RO{\cdot}\ O_2\ {\cdot}OR]\text{cage} \xrightarrow{\text{combination}} R{-}O{-}O{-}R + O_2 \quad (5)$$

$$[RO{\cdot}\ O_2\ {\cdot}OR]\text{cage} \xrightarrow{\text{diffusion}} 2RO\cdot + O_2 \quad (6)$$

$$RO\cdot \xrightarrow{SH} ROH \quad (7)$$

The bulk of experimental evidence indicates that the self-reaction of primary and secondary alkylperoxy radicals proceeds through a concerted process (eq 4a). Several studies, however, have shown that for certain primary and secondary alkylperoxides, a radical process (eq 4b-6) contributes to this mechanism.[22] Our trapping of alkoxy radicals with PBN from a wide variety of primary and secondary alkylperoxy radicals at room temperature suggests that this contribution may be a general phenomenon. The low trapping efficiency (ca. 1%) indicates, however, that this contribution to the $KO_2$-RX reaction is a minor one.

The reactions shown in Scheme I account not only for alkoxy radicals, but for formation of alcohols and aldehydes as well. In contrast, the pathway shown in eq 8 and 9 (Scheme II), originally proposed by Dietz[5] for the demise of alkylperoxy radicals in the $KO_2$-RX reaction, does not account for these products.

**Scheme II**

$$R\text{-}O\text{-}O\cdot + O_2^{-}\cdot \longrightarrow R\text{-}O\text{-}O^{-} + O_2 \quad (8)$$

$$R\text{-}O\text{-}O^{-} + RX \longrightarrow R\text{-}O\text{-}O\text{-}R + X^{-} \quad (9)$$

$$R\text{-}O\text{-}O\text{-}R \xrightarrow{KO_2} ROH \quad (10)$$

Johnson has shown that alcohols may be formed, however, from reduction of dialkyl peroxides with $KO_2$ as illustrated in eq 10.[19] Alkoxy radicals were not generated, as determined by PBN trapping experiments (Table II), in benzene and $Me_2SO$ in this reaction. Furthermore, we found that the peroxide anion, generated from equilibration of 1-pentyl hydroperoxide with KOH or $K_2CO_3$ in the presence of PBN, did not yield the observed alkoxy-PBN spin adducts. These data lead us to conclude that the alkoxy radicals trapped by PBN in the $KO_2$-RX reaction do not originate from the reactions shown in Scheme II. Our data do not permit us to determine the extent the sequence shown in eq 4b-6 contributes to the overall reaction mechanism.

Our inability to trap the initially formed alkylperoxy radicals at room temperature allows us to estimate the rate of the reaction shown in eq 11:

$$R\text{-}O\text{-}O\cdot + PBN \rightarrow R\text{-}O\text{-}O\text{-}PBN \quad (11)$$

The rates of self-reaction (via Scheme I) for primary, secondary, and tertiary alkylperoxy radicals at room temperature are of the order of $2k_t \simeq 3 \times 10^8$, $5 \times 10^6$, and $10^3$-$10^5$ $M^{-1}\ s^{-1}$, respectively.[21] Lack of observation of PBN adducts of the slower self-reacting secondary alkylperoxy radical indicates that the rate of the addition reaction of eq 11 is less than that of self-reaction and, consequently, less than that known for *tert*-butoxy addition to PBN: $5.5 \times 10^6\ M^{-1}\ s^{-1}$.[23]

Dietz et al. estimated the rate of the electron transfer reactions shown in eq 8 to be near the diffusion-controlled limit: $k_2 \simeq 10^9\ M^{-1}\ s^{-1}$.[5] Our observations of PBN-trapped alkoxy radicals along with the known production of aldehydic products suggests that this estimate may be too high and that Scheme I operates, at least in part. The relative contributions of the two schemes may well be a function of solvent and the crown ether.[24]

Comparison of computer simulated spectra with experimental ones containing "impurity" lines indicated that they consisted of a mixture of alkoxy- and alkyl-PBN adducts. These spectra could not be matched by simulations in which mixtures of alkoxy- and alkylperoxy-PBN were assumed. The most likely source of alkyl radicals is from the well-known $\beta$-scission of alkoxy radicals.[25] Alternatively, the carbon-centered radicals may be derived from the crown ether. The production of alkyl radicals from direct electron transfer from superoxide to alkyl bromide is thermodynamically disallowed:

$$O_2^{-}\cdot \rightarrow O_2 + e^{-} \quad E^\circ \simeq +0.8\ \text{V vs. SCE}^{26} \quad (13)$$

$$e^{-} + RBr \rightarrow R\cdot + Br^{-} \quad E^\circ \simeq -2.2\ \text{V vs. SCE}^{27} \quad (14)$$

Therefore,

$$O_2^{-}\cdot + RBr \rightarrow O_2 + R\cdot + Br^{-} \quad E = -1.4\ \text{V vs. SCE} \quad (15)$$

Of ancillary interest is the statistically significant difference in the $\beta$-hydrogen coupling constants of the PBN-alkoxy adducts derived from primary and secondary substrates (Table I). This difference might be exploited in determining the structure of an intermediate alkoxy radical for a given reaction in one solvent.

## Summary

We have shown that alkylperoxy radicals cannot be trapped by PBN except under very limited conditions. Our observations of alkoxy-PBN adducts in the reactions of crown-solubilized $KO_2$ with alkyl halides and sulfonate esters suggest that this reaction proceeds, in part, through self-termination of alkylperoxy radical and that these self-termination reactions involve, in part, a radical mechanism. Product studies further delineating the mechanistic aspect of the crown-solubilized $KO_2$-RX reaction will be published.[19]

## References and Notes

(1) (a) Physical and Analytical Chemistry Research; (b) Experimental Chemistry Research.

(2) (a) For a review of this technique, see E. G. Janzen, *Acc. Chem. Res.*, **4**, 31 (1971); (b) K. U. Ingold, *ibid.*, **9**, 13 (1976).

(3) M. V. Merritt and D. T. Sawyer, *J. Org. Chem.*, **35**, 2157 (1970).

(4) J. San Filippo, Jr., C. I. Chern, and J. S. Valentine, *J. Org. Chem.*, **40**, 1678 (1975).

(5) R. Dietz, A. E. J. Forno, B. E. Larcombe, and M. E. Peover, *J. Chem. Soc. B*, 816 (1970).

(6) R. A. Johnson and E. G. Nidy, *J. Org. Chem.*, **40**, 1680 (1975).

(7) J. A. Weil and J. K. Anderson, *J. Chem. Soc.*, 5567 (1965).

(8) M. Iwamura and N. Inamota, *Bull. Chem. Soc. Jpn.*, **40**, 702 (1967); **43**, 856 (1970).

(9) K. S. Chen, private communication.

(10) H. R. Williams and H. S. Mosher, *J. Am. Chem. Soc.*, **76**, 2984 (1954).

(11) P. D. Bartlett and J. M. McBride, *J. Am. Chem. Soc.*, **87**, 1727 (1965).

(12) S. Wawzonek, P. D. Klimstra, and R. E. Kallio, *J. Org. Chem.*, **25**, 621 (1960).

(13) A. R. Forrester and S. P. Hepburn, *J. Chem. Soc. C*, 701 (1970).

(14) P. D. Bartlett and G. Guaraldi, *J. Am. Chem. Soc.*, **89**, 4799 (1967).

(15) M. Bersohn and J. R. Thomas, *J. Am. Chem. Soc.*, **86**, 959 (1964).

(16) A. L. Bluhm and J. Weinstein, *J. Org. Chem.*, **37**, 1748 (1972).

(17) E. J. Corey, K. C. Nicolau, M. Shibasaki, Y. Machida, and C. S. Shiner, *Tetrahedron Lett.*, 3183 (1975).
(18) J. R. Harbour, V. Chow, and J. R. Bolton, *Can. J. Chem.*, **52**, 3549 (1974).
(19) R. A. Johnson, to be published.
(20) J. W. Peters and C. S. Foote, *J. Am. Chem. Soc.*, **98**, 873 (1976).
(21) K. U. Ingold, *Acc. Chem. Res.*, **2**, 1 (1969).
(22) (a) D. Lindsay, J. A. Howard, E. C. Horswill, L. Iton, K. U. Ingold, T. Cobbley, and A. Li, *Can. J. Chem.*, **51**, 870 (1973); (b) J. A. Howard and J. E. Bennett, *ibid.*, **50**, 2374 (1972); (c) D. G. M. Diaper, *ibid.*, **46**, 3095 (1968).
(23) E. G. Janzen and C. A. Evans, *J. Am. Chem. Soc.*, **95**, 8205 (1973).
(24) Y. Chang, G. Bruno, and M. Eastman, Abstracts, 172nd National Meeting of the American Chemical Society, San Francisco, Calif., Sept 1976, No. PHYS-23.
(25) J. K. Kochi in "Free Radicals", Vol. II, J. Kochi, Ed., Wiley, New York, N.Y., 1974, pp 665–716.
(26) D. L. Maricle and W. G. Hodgson, *Anal. Chem.*, **37**, 1562 (1965).
(27) F. L. Lambert and K. Kobayashi, *J. Am. Chem. Soc.*, **82**, 5324 (1960).

# Benzidine Rearrangement. 14. The Nitrogen Kinetic Isotope Effect in the Acid-Catalyzed Rearrangement of Hydrazobenzene[1,2]

**Henry J. Shine,*[3a] George N. Henderson,[3a,b] Alexander Cu,[3a,b] and Peter Schmid[3c,4]**

*Contribution from the Department of Chemistry, Texas Tech University, Lubbock, Texas 79409, and Department of Chemistry, McMaster University, Hamilton, Ontario, L8S 4L8, Canada.*

*Received November 5, 1976*

**Abstract:** Rearrangement of hydrazobenzene was carried out at 0 °C in ~75% aqueous ethanol which was 0.1 M in HCl. Rearrangement products were isolated at 10, 20, 30, and 100% extents of rearrangement and converted into nitrogen gas whose $^{29}N_2/^{28}N_2$ contents were determined by isotope-ratio mass spectrometry. By this means the rearrangement was found to have a kinetic nitrogen isotope effect ($k^{14}/k^{15}$) of 1.0203 ± 0.0007, demonstrating that breaking of the N–N bond in this two-proton rearrangement is part of the rate-determining step. The result is inconsistent with two mechanisms of the rearrangement which are found in the literature: the rate-determining formation of $C_6H_5N^+H_2N^+H_2C_6H_5$ followed by its rapid rearrangement; and rate-determining second protonation at C-1 carbon atom followed by the rearrangement of the ring-protonated dication. The isotope effect result is consistent with two pathways but cannot distinguish between them: preequilibrium diprotonation at the two nitrogen atoms followed by the rate-determining rearrangement of $C_6H_5N^+H_2N^+H_2C_6H_5$; and the rate-determining concerted scission of the N–N bond and approach of the second proton to $C_6H_5N^+H_2NHC_6H_5$, the second proton being almost but not completely transferred in the transition state.

Although a great deal is known and has been written about the acid-catalyzed benzidine rearrangements,[5] a completely satisfying understanding of their mechanisms is still not at hand. It is recognized and now universally accepted that two classes of acid catalysis exist, commonly called one-proton and two-proton rearrangements. These terms signify that some rearrangements are kinetically first order while others are second order in acid. It is also recognized that a particular rearrangement may at low acidities exhibit first order, and at higher acidities exhibit second-order acid catalysis. All rearrangements, of course (at least, to date), are first order in hydrazoaromatic.

For some years these kinetic features were described with widespread, but not total, acceptance by eq 1–4.

$$\mathrm{ArNHNHAr + H^+ \rightleftarrows ArN^+H_2NHAr} \quad \text{(fast)} \quad (1)$$

$$\mathrm{ArN^+H_2NHAr \rightarrow product^+} \quad \text{(slow)} \quad (2)$$

$$\mathrm{ArN^+H_2NHAr + H^+ \rightleftarrows ArN^+H_2N^+H_2Ar} \quad \text{(fast)} \quad (3)$$

$$\mathrm{ArN^+H_2N^+H_2Ar \rightarrow product^{2+}} \quad \text{(slow)} \quad (4)$$

The equations require that the protonations of steps 1 and 3 are fast and reversible, a conclusion which had been developed principally from the solvent-isotope work of Banthorpe, Hughes, and Ingold,[5c] and that rearrangements involve the rate-determining scission of the N–N bond. The major unsolved question in benzidine rearrangements appeared for a long time to be, therefore, how steps 2 and 4 occurred; that is, how indeed the mono-N-protonated and di-N,N′-protonated molecules underwent intramolecular rearrangement. It was the seeking of answers to this question which culminated in the several theories of rearrangement; the polar transition state theory,[5c] the π-complex theory,[5a,b] and the cation-radical theory, among which the first appeared to hold the field.[5d,h]

There were some early critics of the idea that the second protonation at nitrogen (step 3) would be fast and reversible. Dewar had incorporated in his original π-complex theory of rearrangement a slow, rate-determining approach of the second proton , an approach which caused a monocationic π complex to reorganize into the product.[5a] Lukashevich,[6] on the basis that, while a hydrazobenzene monochloride was isolable a dihydrochloride was not, also proposed that a second protonation could not occur, but instead that the second proton caused rearrangement to occur during the progress of its approach to the monocation. These proposals were for the most part critically rejected, the rate-determining protonation one because there was no supporting kinetic evidence,[5c,d,7] and the π-complex one because it contradicted in some of its other aspects other features of benzidine rearrangements.[5c,d] More definitive proposals of slow proton transfer for the second protonation were made by Cohen and Hammond[8] and Vecera, Synek, and Sterba.[9] In the former case the rearrangement of hydrazobenzene was classified, from work with buffered solutions, as exhibiting general rather than specific acid catalysis. In the latter case the option for slow proton transfer was made from the effects of acidity and solvent on the kinetics and composition of products of rearrangement of hydrazobenzene. Both groups acknowledged, also, that it was not kinetically possible to distinguish between two processes, eq 5 and 6 and eq 7.

$$\mathrm{C_6H_5N^+H_2NHC_6H_5 + HA \rightarrow C_6H_5N^+H_2N^+H_2C_6H_5} \quad \text{(slow)} \quad (5)$$

*Shine et al. / Rearrangement of Hydrazobenzene*