straight line to at least 80% reaction. From the slope of this line, k_{obsd} was obtained. As described in the text, plots were then made of k_{obsd} vs. (entering ligand) and $1/k_{obsd}$ vs. 1/(entering ligand). The best line through the data points was obtained in the latter plot by a linear least-squares data fit program. The methods for obtaining the rate constants from these plots are described in the text. Extinction coefficients at the wavelengths mentioned are given in Table IV for all compounds studied, and using these, overall equilibrium constants were measured.

Acknowledgment. Financial support from the National Institutes of Health (GM-15373) is gratefully acknowledged.

References and Notes

(1) National Science Foundation Predoctoral Fellow, 1970–1973.
(2) W. H. Pailes and H. P. C. Hogenkamp, *Biochemistry*, **7**, 4160 (1968).
(3) B. M. Babior, *J. Biol. Chem.*, **245**, 6125 (1970).
(4) C. H. Langford and H. B. Gray, "Ligand Substitution Processes", W. A. Benjamin, New York, N.Y., 1965.
(5) C. K. Poon, *Coord. Chem. Rev.*, **10**, 1 (1973).
(6) A. L. Crumbliss and W. K. Wilmarth, *J. Am. Chem. Soc.*, **92**, 2593 (1970).
(7) (a) L. M. Ludwick and T. L. Brown, *J. Am. Chem. Soc.*, **91**, 5188 (1969); (b) T. L. Brown, L. M. Ludwick, and R. S. Stewart, *ibid.*, **94**, 384 (1972).
(8) K. L. Brown and R. G. Kallen, *J. Am. Chem. Soc.*, **94**, 1894 (1972).
(9) A. W. Herlinger and T. L. Brown, *J. Am. Chem. Soc.*, **94**, 388 (1972).
(10) G. Costa, G. Mestroni, G. Tauzher, D. M. Goodall, M. Green, and H. A. O. Hill, *Chem. Commun.*, **34** (1970).
(11) G. Tauzher, R. Dreos, G. Costa, and M. Green, *J. Chem. Soc., Chem. Commun.*, 413 (1973).
(12) E. G. Fleischer, S. Jacobs, and L. Mestichelli, *J. Am. Chem. Soc.*, **90**, 2527 (1968).
(13) A. Haim, R. J. Grassi, and W. K. Wilmarth, *Adv. Chem. Ser.*, **No. 49**, 31 (1965).
(14) G. N. Schrauzer and R. J. Windgassen, *J. Am. Chem. Soc.*, **88**, 3738 (1966).
(15) The NMR spectrum of methyl(4-dimethylaminopyridine)cobaloxime in $CDCl_3$ shows only one amino-methyl peak (δ 2.97, s) and one ligand methyl absorbance (δ 2.12, s). This is taken as evidence that only one compound is present. Due to the fact that the pyridine nitrogen atom is more basic and more sterically accessible, coordination of it to the cobalt is assumed. However, it is still quite possible that reversible coordination of the anilino nitrogen occurs during the exchange process although the product involving such coordination is not thermodynamically favored.
(16) A. Fischer, W. J. Galloway, and J. Vaughan, *J. Chem. Soc.*, 3591 (1964).
(17) In that the reaction center is obtained within the ring a ρ value considerably larger would be expected.[18] For the dissociation of pyridinium ions, a value of $\rho = +6.01$ has been reported.[16]
(18) R. W. Taft, Jr., *J. Phys. Chem.*, **64**, 1809 (1960).
(19) F. A. Walker, *J. Am. Chem. Soc.*, **95**, 1150 (1973).

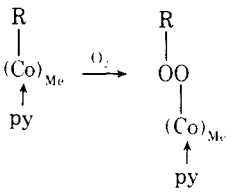
Stereochemistry and Mechanism of the Photochemical and Thermal Insertion of Oxygen into the Carbon–Cobalt Bond of Alkyl(pyridine)cobaloximes[1]

Frederick R. Jensen* and Ronald C. Kiskis[2]

Contribution from the Department of Chemistry, University of California, Berkeley, California 94720. *Received August 9, 1974*

Abstract: Photochemically induced insertion of oxygen into the carbon–cobalt bond of optically active 2-butyl(pyridine)cobaloxime occurs with complete racemization. Similarly, and in contrast to a previous report, both the photochemical and thermal reactions with optically active 2-hydroxy-1-phenethyl(pyridine)cobaloxime yield no optically active dioxy product. The apparent difference in results between this and previous work is believed to arise from the practical difficulties of measuring optical rotations of highly colored solutions. Photolysis of 5-hexenyl(pyridine)cobaloxime under suitable conditions yields almost entirely the cyclized product cyclopentylmethyldioxy(pyridine)cobaloxime. The cyclization of the 5-hexenyl radical to the cyclopentylmethyl radical is well documented, and the formation of cyclized product is evidence that the reaction proceeds through the intermediacy of free radicals. Evidence regarding possible mechanisms was obtained. Addition of pyridine significantly retards the rate of axial pyridine ligand exchange by tri-*n*-butylphosphine, which indicates that ligand exchange occurs through a dissociative mechanism. However, addition of excess pyridine does not affect the rate of the oxygen insertion reaction, and this eliminates several previously proposed mechanisms which have involved the formation of a "base-off" complex during the oxygen insertion process. The preferred mechanism for the photolytic reaction involves a base-off complex, but it arises differently than has been suggested earlier. In contrast, the thermal reaction does not proceed through the base-off complex. In addition, photochemically induced ligand exchange is demonstrated for these complexes.

Considerable current interest exists in the reaction between cobalt complexes and molecular oxygen.[3-9] Recently, Gaudemer and coworkers have shown that, in the presence of oxygen, stable dioxy adducts can be obtained from alkyl(pyridine)cobaloximes.[10] When R is a benzylic or allylic



(1)

moiety, the insertion reaction proceeds either thermally in the dark or photochemically.[11] Simple alkyl derivatives do not react at moderate temperatures except when irradiated.[12] The reactions proceed well regardless of the R group, and there is no report of an organocobaloxime that does not give the dioxy product when treated as described. The thermal (dark) reactions are generally carried out at room temperature, while the photolysis reactions may be carried out at lower temperatures using light filtered through copper sulfate solution.[13]

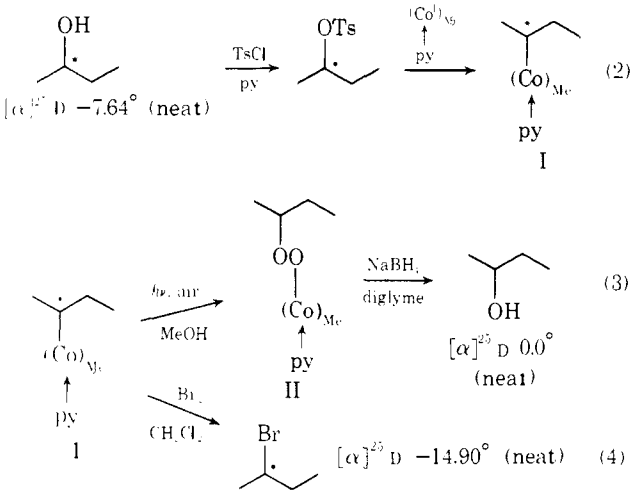
This facile reaction gives quantitative yields in some cases[1,10] and has been reported to be stereospecific,[10,14] with an assignment of possible stereochemistry in one case.[14] This observation has important biochemical and mechanistic[15] implications. The alkylcobaloximes serve as models for coenzyme B_{12},[17] and several proposed mechanisms for conversions mediated by B_{12} involve alkylcobalt complexes as intermediates. Some transformations catalyzed by B_{12} dependent enzymes including propanediol

dehydrase,[18a] ethanolamine ammonia-lyase,[18b] methylmalonyl CoA isomerase,[18c] and glutamate mutase[18d] occur stereospecifically even though, in at least two of these cases, evidence has been presented indicating the presence of alkyl radical intermediates. Therefore, the study of reactions of alkylcobaloximes that might proceed without loss of stereochemistry could prove to be valuable in understanding the mechanisms of these B_{12} dependent transformations. With these considerations in mind, the stereochemistry and mechanism of the reaction have been investigated.

Results and Discussion

Stereochemistry. Optically active 2-butyl(pyridine)cobaloxime (I)[19] was photolyzed in methanol in the presence of air to give, after purification, a 75% yield of 2-butyldioxy(pyridine)cobaloxime (II). Compound II was cleaved with excess sodium borohydride[10] to give racemic 2-butanol in 61% yield. It was determined that loss of stereochemistry did not occur by racemization after reduction by adding optically active 2-butanol to the reaction mixture and recovering active 2-butanol after reduction. The assumption must be made that the reduction does not lead to racemization of the α carbon. However, it has been previously demonstrated that metal hydride reductions of the peroxidic linkage in optically active 1-phenethyl hydroperoxide, a closely related compound, proceeds without racemization.[20] It was shown that the starting 2-butyl(pyridine)cobaloxime was optically active by bromodemetallation, a process known to occur with inversion of configuration at the asymmetric carbon.[19] The full sequence of reactions is shown in Scheme I.

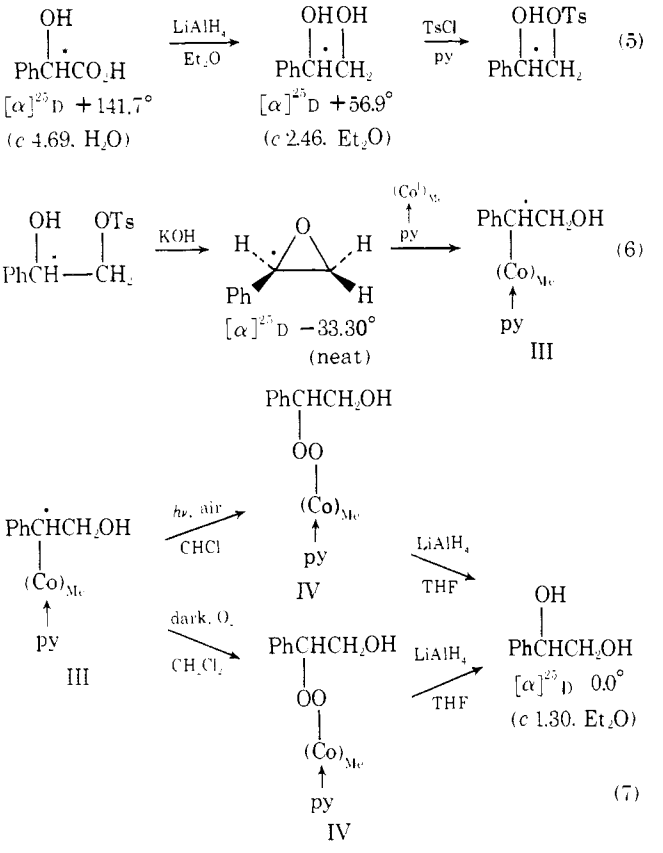
Scheme I



It was reported previously[10] that the oxygen insertion reaction proceeded stereospecifically with optically active 2-hydroxy-1-phenethyl(pyridine)cobaloxime. Because of the fact that this conflicts with the results obtained above with the optically active 2-butyl(pyridine)cobaloxime, a reinvestigation was thought to be worthwhile.

2-Hydroxy-1-phenethyl(pyridine)cobaloxime (III) undergoes the oxygen insertion reaction both photochemically and thermally (dark), because it possesses a benzylic carbon-cobalt bond. For the photochemical reaction, a chloroform solution of optically active compound III was photolyzed at −5° in the presence of air. The yield of dioxy product IV was quantitative. Reduction with lithium aluminum hydride in THF (sodium borohydride gave little or no yield of phenyl-1,2-ethanediol) gave racemic phenyl-1,2-ethanediol in 30% yield. As before when optically active phenyl-1,2-ethanediol was added to the reduction mixture, active diol was isolated.

Scheme II



For the stereochemical study of the thermal reaction, optically active compound III dissolved in methylene chloride was subjected to a positive pressure of oxygen in the dark. Isolation of the dioxy product, followed by reduction with $LiAlH_4$, produced racemic phenyl-1,2-ethanediol. The results are summarized in Scheme II.

In both the above studies, compound III was shown to be optically active by measuring its rotation on a Bendix 143-A (Faraday effect) polarimeter. Chloroform solutions with 46% transmittance gave definite rotations, but the values were not reproducible and fluctuated within a given measurement presumably due to slow thermal decomposition.[21] The rotation of the dioxy compound IV isolated from the photochemical reaction was found to be zero when solutions with 43% transmittance were measured.

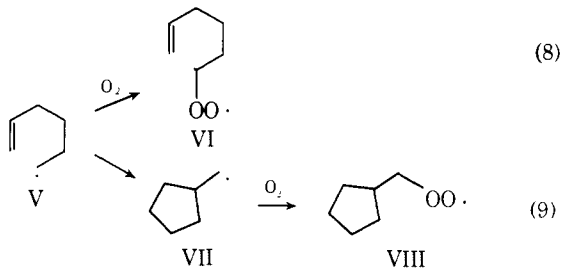
The earlier research concerning the oxygen insertion reaction suggested that it proceeds without racemization at the carbon originally bound to cobalt. With *trans*-2-hydroxy-1-indanyl(pyridine)cobaloxime, retention of configuration was observed, but results with the cis isomer were not included.[14] Since one must examine results from both isomers when using geometrical isomers to determine the stereochemistry of a reaction, drawing a meaningful conclusion from the above observation is impossible. As mentioned above, optically active 2-hydroxy-1-phenethyl(pyridine)cobaloxime (III) was reported to react with oxygen to form optically active 2-hydroxy-1-phenethyldioxy(pyridine)cobaloxime (IV).[10] These compounds were claimed to be optically active on the basis of observed rotations. Both complexes are highly colored and absorb at the wavelength used to measure the rotation (589 nm): compound III, ϵ_{589} 34; compound IV, ϵ_{589} 92, both in $CHCl_3$.[22] Measurement of rotation was done at high enough concentration that most of the light was absorbed and, in fact, the solution of com-

pound IV was essentially opaque and would most likely give a false or "ghost" rotation if the detector in the polarimeter were a photocell. Such ghost rotations are in fact observed at the indicated concentration with the Bendix instrument and have previously been observed in unpublished results with other compounds utilizing a Zeis (photocell detector) polarimeter.

Mechanism. As was suggested previously,[1] the above studies are consistent with a mechanism involving generation of an alkyl radical at some point during the insertion process. In that these radicals are achiral, loss of stereochemistry would result. In order to test the hypothesis concerning the formation of radicals during the reaction, the photolysis of 5-hexenyl(pyridine)cobaloxime was studied.

The 5-hexenyl radical has been shown to cyclize to the cyclopentylmethyl radical.[23] This has been used in several cases as a mechanistic probe to detect the intermediacy of radical species.[24,25,26] In the presence of oxygen, peroxy radicals VI and VIII may be obtained either from the parent 5-hexenyl radical (V) (Scheme III) or from its cyclized

Scheme III



form, the cyclopentylmethyl radical (VII). Since the formation of VI, but not VII, has a first-order dependence on the oxygen concentration, the VI/VII ratio (and the VI/VIII ratio) is proportional to the concentration of oxygen (oxygen present in large excess or at constant concentration). This prediction has been tested experimentally in the autoxidation of Grignard compounds and found to be valid.[24]

Photolysis of 5-hexenyl(pyridine)cobaloxime under the appropriate conditions should lead to the formation of significant amounts of cyclopentylmethyldioxy(pyridine)cobaloxime if the oxygen insertion reaction proceeds through a free radical.[27,28] Benzene, being fairly unreactive toward radicals, was used as solvent.

The results in Table I are consistent with the expected behavior of alkyl radicals as reaction intermediates. In comparing the data of experiments 1 and 2, it is evident that the higher the oxygen concentration, the lower the relative amount of cyclized product. It should also be noted that, as one would predict, the overall yield increases in going from 1 to 2 because of the increased efficiency of oxygen in trapping alkyl radicals,[29] and thus decreasing the extent of side reactions such as dimerization and disproportionation.

In addition to the results given in Table I, the course of the reactions was followed by NMR spectroscopy with similar findings. The NMR data for the purified compounds are shown in Table II. The spectrum of the mixture from experiment 1 is effectively identical with that of cyclopentylmethyldioxy(pyridine)cobaloxime, indicating almost complete cyclization. The spectrum of the mixture from experiment 2 contains vinylic absorptions with intensity indicating three hydrogens. The peroxymethylene absorbance occurs at δ 3.29 and is a crude triplet. Both observations are consistent with the uncyclized structure.

From the preceding results, it is clear that the oxygen insertion reaction proceeds through a free alkyl radical which then rapidly combines with oxygen in a bimolecular process. In addition to providing information on the nature of the oxygen insertion reaction, the photolysis of 5-hexenyl(pyridine)cobaloxime provides the strongest evidence presented to date that irradiation of alkylcobaloximes produces alkyl radicals and cobaloxime(II).[19,30,31,31a]

Table I. Yield Data for 5-Hexenyl(pyridine)cobaloxime Cyclization

Expt	Conditions	Alkyldioxycobaloxime products, %[a] Cyclized[b]	Open[c]	Overall[d] yield
1	$h\nu$, 35°, air atmosphere	91	9	51
2	$h\nu$, 35°, O_2 bubbled through at 10 ml/min	4	96	67

[a] Cyclized and uncyclized products were determined by reduction of the dioxycobaloxime with $NaBH_4$ and GLC and NMR analysis of the alcohol products and comparison with known materials. [b] Cyclopentylmethyldioxy(pyridine)cobaloxime. [c] 5-Hexenyldioxy(pyridine)cobaloxime. [d] Combined yields of the cyclized and open dioxycobaloximes. Yields reported are after isolation and purification.

Table II. NMR Data for 5-Hexenyl(pyridine)cobaloxime Cyclization Reactions[a]

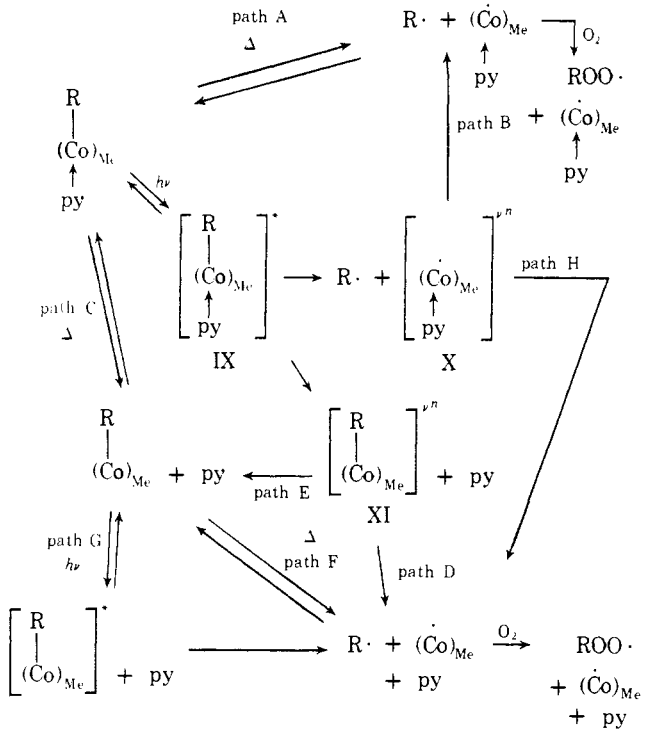
Compd	dmg methyl	Olefinic peaks	Peroxymethylene
5-Hexenyl(pyridine)-cobaloxime	2.12 (12 H, s)	4.7–6.2 (3 H, m)	None
Cyclopentylmethyldioxy(pyridine)-cobaloxime	2.30 (12 H, s)	None	3.22 (3 H, d (6 Hz))
Mixture from expt 1 (Table I)[b]	2.30 (12 H, s)	Almost none	3.22 (3 H, d (6 Hz))
Mixture from expt 2 (Table I)[b]	2.30 (12 H, s)	4.8–6.2 (3 H, m)	3.29 (3 H, t)

[a] Resonances expressed as δ (Me_4Si). [b] Purified by chromatography on silica gel.

In light of the conflicting suggestions made by others, a study of the mechanism of the photolysis reaction was undertaken. Schrauzer has proposed, based in part on molecular orbital calculations,[31] that photolysis of alkylcobaloximes leads to excitation and subsequent homolytic cleavage of the carbon–cobalt bond. Giannotti and coworkers have suggested that photolysis with light in the charge-transfer region (about 450 nm) leads to expulsion of the axial base as the primary photochemical process. When run in aqueous solvents, they claim[32,33] that pyridine is photoexpelled and replaced by water. In the oxygen insertion reaction, they proposed that this alkyl(aquo)cobaloxime undergoes the oxygen insertion reaction directly,[33] or that the water base dissociates and the resulting pentacoordinate alkylcobaloxime inserts oxygen.[32] In the absence of water, it was suggested that photolysis yields the base-off species directly and that this absorbs light again during the actual oxygen insertion process.[34]

Within the framework shown in Scheme IV, eight possible partial mechanisms can be delineated, and these are named according to the "paths" through which they proceed. (Mechanisms: A, B, C-F, C-G, D, E-F, E-G, and H.) All the steps in mechanisms A and C-F are thermal and hence are only viable for those complexes that do not require light to react, such as the benzylic derivatives. Mechanism A involves a thermal carbon–cobalt bond homolysis followed by the trapping of the alkyl radical by oxygen, while mechanism C-F involves thermal base dissociation preceding bond homolysis. The six remaining mecha-

Scheme IV



nisms all require light for one or more of the steps. Mechanism B entails an initial photochemical excitation to a higher electronic state, complex IX. This is followed by carbon–cobalt bond rupture and subsequent loss of excess energy to solvent from a vibrationally excited ground electronic state complex, compound X.[35] Complex X can also expend its excess energy to produce the base-off cobalt(II) complex (mechanism H). Complex IX may convert to complex XI which is also in a ground electronic state but high energy vibrational state. This excess vibrational energy can either be dissipated by carbon–cobalt bond homolysis (path D) or transfer to the surrounding solvent (path E). After path E, the base-off complex can either revert to starting material or proceed to product by a photochemical process (mechanism E–G) or a thermal process (mechanism E–F). The last mechanism (C–G) involves thermal pyridine dissociation to give the base-off complex followed by the photochemically induced carbon–cobalt bond homolysis. For complex IX, the electronic state is not specified, and more than one excited electronic state may be involved during the conversions. The salient features of the mechanisms which proceed through complexes IX, X, and XI are their nonreversibility and the transformation from an excited electronic state to an excited vibrational (ground electronic) state.

For the photochemical process, mechanisms A and C–F can be eliminated since they only involve thermal steps. Mechanism E–F can be eliminated because, at temperatures near room temperature, the pyridine base dissociates rapidly,[36] but simple alkyl(pyridine) cobaloximes do not insert oxygen in the dark. Mechanism C–G is also easily eliminated by two simple experiments. If the first step is thermal as this mechanism suggests, then the reaction cannot proceed at temperatures where there is no thermal dissociation of the pyridine. When a chlorobenzene solution of 5-hexenyl(pyridine)cobaloxime containing some $P(n\text{-Bu})_3$[36] is allowed to stand in the dark at −25° for 0.5 hr, no pyridine exchange occurs. Photolyzing the sample at −25° with oxygen present readily leads to formation of the dioxy product. Hence, the above mechanism C–G is incorrect.

Mechanism E–G involves light both for the base dissociation as well as the bond homolysis and is more difficult to test. Simple kinetics leads to the prediction that adding pyridine to the oxygen insertion reaction solution will slow down the observed rate of conversion of starting material, provided that the reverse path C is comparable to or faster than the rate of path G. If reverse path C is much slower, then adding pyridine will have no effect provided $k_G \gg k_{-C}[\text{pyr}]$, that is provided path G remains much faster than reverse path C. No effect will be seen by adding pyridine if path G is zero order in base-off species, however. This is true whether or not reverse path C is slower. In that path G is a photochemical step in this mechanism, the rate expression for this step will not contain a base-off concentration term if this species is present in high enough concentration so that it absorbs all the incident light at the critical wavelength. Hence, the reaction where excess pyridine is added must be run under conditions where not all the light would be absorbed by the base-off species if it were formed. 5-Hexenyl(pyridine)cobaloxime was photolyzed at a starting concentration of 2.22×10^{-4} M in air-saturated benzene. Even if at some given time all the cobaloxime were in the base-off form and it had an extinction coefficient[37] of 1.5×10^3, 47% of the light would pass through.[38] After 11 min at room temperature, the reaction mixture yielded 70% dioxy product and 30% starting material. Using the identical procedure except that the reaction solution contained a 100-fold excess of pyridine gave 69% dioxy product and 31% starting material. Thus, there is no effect on the rate of reaction by adding pyridine indicating that, if the base-off species is formed, it goes on to products much faster than it recombines with pyridine. The mechanism can now be disproved if it can be shown that the base comes off thermally much faster than the reaction proceeds. The rates of interest here are $k_{-C}[\text{pyr}][\text{R-(CO)}_{\text{Me}}]$ and $\Phi I[\text{R-(CO)}_{\text{Me}}]$. The ratio is $k_{-C}[\text{pyr}][\text{R-(CO)}_{\text{Me}}]/\phi I[\text{R-(CO)}_{\text{Me}}]$ and by the fact that added pyridine has no effect on the rate then $k_{-C}[\text{pyr}][\text{R-(Co)}_{\text{Me}}] \gg \Phi I[\text{R-(Co)}_{\text{Me}}]$. However, the term $k_{-C}[\text{pyr}][\text{R-(Co)}_{\text{Me}}]$ equals $k_C[\text{R-(Co)}_{\text{Me}}\text{-py}]$ at equilibrium, and hence knowing the rate of the forward reaction will also give the rate of the reverse reaction provided the equilibrium is established. If this rate is greater than the rate of dioxy product formation, the mechanism cannot be correct. Excess $P(n\text{-Bu})_3$ was added to a benzene solution of 5-hexenyl(pyridine)cobaloxime (4.2×10^{-2} M) at room temperature in the dark. Complete exchange occurs in less than 30 sec. Thus, formation of the base-off species, and hence the reverse reaction, is faster than dioxy product formation, showing mechanism E–G to be inoperative.

Three mechanisms (B, D, and H) remain as possibilities. If product formation involves either mechanism D or H, photolysis under anaerobic conditions would cause axial base exchange if another base were present. In contrast, if only B is involved, no base exchange would occur upon photolysis, and starting material would be recovered. The above predictions hold only if the reverse of paths A and F can occur.[39] In that the reversibility of the homolysis has been fairly well demonstrated by radical trapping experiments,[3,4,8] this does not present a problem. When 5-hexenyl(pyridine)cobaloxime (3.3×10^{-2} M) was photolyzed along with threefold excess $P(n\text{-Bu})_3$ in chlorobenzene under N_2 (anaerobic conditions) at −28° for 30 min, 20% of the starting material was converted to 5-hexenyl(tri-*n*-butylphosphine)cobaloxime. Under identical conditions except with oxygen bubbling through the solution and no $P(n\text{-Bu})_3$ present, a 20% yield of 5-hexenyldioxy(pyridine)cobaloxime was obtained. No thermal axial base exchange occurs under these conditions. These experiments provided evidence that photochemically induced ligand ex-

change does occur. They also suggest that ligand dissociation may precede the step involving oxygen insertion making mechanism **D** attractive. It is not unlikely, however, that ligand dissociation is not a requirement for the oxygen insertion to occur. That is, it is possible that, while the ligand can be exchanged by photolysis (path E), the actual oxygen insertion process proceeds only through ligand-intact complex, mechanism B.

It was impossible to run the oxygen insertion reaction in the presence of tri-*n*-butylphosphine because of the fact that the phosphine reacts with oxygen. Therefore a similar experiment involving an oxygen insensitive base was preformed in the attempt to determine the mechanism of the reaction. Three compounds were formed when a solution of methyl(pyridine)cobaloxime (6.7×10^{-2} *M*) in chlorobenzene containing a threefold excess of 4-acetylpyridine was photolyzed at −25° for 3 hr. About 20% conversion occurred, and a 3:1 ratio of methyldioxy(4-acetylpyridine)cobaloxime and methyldioxy(pyridine)cobaloxime, along with a small amount of methyl(4-acetylpyridine)cobaloxime, was produced. Had (essentially) only one of the dioxy products been formed, additional evidence for one of the possible mechanisms may have been provided. These experimental results do not even eliminate the possibility that mechanism B is the only pathway for dioxy product formation (even though 4-acetylpyridine-based dioxy product is found) because light also induces ligand exchange in the dioxy complexes.[32]

It is not obvious how to adequately distinguish the three remaining mechanisms (B, D, and H) without doing a much more detailed analysis. A monochromatic light source would be necessary for the kinetics to be studied properly. Of more significance than the detailed mechanism, however, is the fact that the two photochemical processes characteristic of transition metal complexes, homolytic cleavage and ligand exchange, are conclusively demonstrated for these compounds.

For the determination of the mechanism of the thermal (dark) oxygen insertion reaction, the same general approach was followed in attempting to establish the possible importance of the base-off species. Pyridine has no effect on the rate at room temperature when added to the reaction mixture containing 2-hydroxy-1-phenethyl(pyridine)cobaloxime in benzene under a positive pressure of oxygen. This indicates that either the base-off species is formed in the rate-determining step or it is not involved. The situation was found to be the latter by the observation that the base comes off much faster than the oxygen insertion reaction occurs. In the ligand-intact mechanism (A), carbon–cobalt bond cleavage does not depend on the presence of oxygen. The observation that 2-hydroxy-1-phenethyl(pyridine)cobaloxime completely decomposes in benzene solution at room temperature under nitrogen in the time required for the oxygen insertion to occur provides further support for mechanism A.

Experimental Section

All cobaloximes were synthesized according to standard procedures.[40] Optically active 2-butyl(pyridine)cobaloxime was made according to a previously described method.[19] The optically active 2-hydroxy-1-phenethyl(pyridine)cobaloxime, cyclopentylmethyl(pyridine)cobaloxime, and 5-hexenyl(pyridine)cobaloxime were obtained as described below. Bromodemetallation of optically active 2-butyl(pyridine)cobaloxime was carried out according to a previously published procedure.[19] All other materials used were commercially available. Optical rotations were measured on either a Bendix 143-A (Faraday effect) polarimeter with a 1-cm cell or a Zeiss photoelectric polarimeter with a 10-cm cell. NMR spectra were taken on a Varian T-60 or HA-100 instrument. All cobalt compounds gave satisfactory elemental analyses, and their spectra are in accord with the assigned structures.

Optically Active 2-Hydroxy-1-phenethyl(pyridine)cobaloxime. D-(+)-Mandelic acid, $[\alpha]^{25}D$ +141.7° (*c* 4.69, H_2O), was used as obtained from Aldrich Chemical Co. The acid, 44.0 g (0.29 mol), was reduced in 600 ml of ethyl ether with 24.3 g (0.64 mol) of $LiAlH_4$ to give, after isolation and recrystallization from benzene–petroleum ether, a 60% yield of the optically active phenyl-1,2-ethanediol, $[\alpha]^{25}D$ +56.9° (*c* 2.46, Et_2O).[41] A solution of 11.81 g (86 mmol) of the diol in 100 ml of purified pyridine was cooled to about 3° followed by the addition of 16.4 g (86 mmol) of *p*-toluenesulfonyl chloride.[42] The reaction solution was stirred for 18 hr at 3° and then poured into 200 ml ice and water. Ether was added, and the layers were separated. The aqueous layer was washed with ether, and then all the ether extracts were combined, washed with 15% HCl and then with water, and finally dried with sodium sulfate. The ether was stripped off at 20°, leaving a white solid. This solid was shown by NMR to be 2-phenyl-1,2-ethanediol-1-tosylate, with no apparent impurities, in 89% yield. The crude tosylate, 23.3 g (80 mmol), was dissolved in 150 ml of methanol in a 500-ml three-necked flask fitted with two dropping funnels and an N_2 inlet. About 50 ml of water was added, and the system was flushed with N_2. The contents of the two funnels, one with 4.7 g (80 mmol) of KOH dissolved in 75 ml of methanol and the other with 175 ml of reagent grade mixed hexanes, were added simultaneously over a period of about 20 min. After stirring for an additional 30 min, the entire reaction mixture was filtered and the filtrate added to a separatory funnel along with about 100 ml of water. The layers were separated, and the aqueous layer was extracted with hexanes. The hexanes layer were combined, washed with water, and dried with sodium sulfate. Stripping off the solvent left a pale yellow liquid which when distilled gave 6.1 g (57%) of styrene oxide {[bp 74.5–75.5° (10.5 mm) [lit.[41] bp 62–63° (4.5 mm) $[\alpha]^{25}D$ −33.30° (neat)]}.[41] The styrene oxide was reacted with cobaloxime(I)[40] to yield the optically active 2-hydroxy-1-phenethyl(pyridine)cobaloxime as previously reported.[10]

5-Hexenyl(pyridine)cobaloxime. 5-Hexen-1-ol (Matheson Coleman and Bell), 5.0 g (50 mmol), was stirred along with 4.02 g (50.8 mmol) of pyridine and 9.7 g (50.8 mmol) of *p*-toluenesulfonyl chloride at 3° in 90 ml of CH_2Cl_2 for 1 week. The reaction solution, colorless with a precipitate of pyridine hydrochloride, was poured into 250 ml of ice and water and the organic layer separated. The water layer was extracted with 75 ml of CH_2Cl_2, and the organic solutions were combined. This was washed successively with cold, dilute HCl, dilute NaOH, and finally water. It was dried with $MgSO_4$ and the CH_2Cl_2 stripped off, leaving the colorless liquid product. NMR revealed this to be 5-hexenyltosylate, crude yield 11.58 g (91%). This material was reacted directly with cobaloxime(I) to give, after purification by column chromatography (silica gel, elution with 1:1:1 MeOH–EtOAc–$CHCl_3$), 5-hexenyl(pyridine)cobaloxime: NMR ($CDCl_3$) δ 0.6–2.0 (broad multiplets), 2.1 (singlet, Me of DMG), 4.8 and 5.0 (multiplets, $=CH_2$), 5.3–5.8 (multiplet —CH=), 7–8.6 (multiplets, pyridine).

Anal. Calcd. for $C_{19}H_{30}N_5O_4Co$: C, 50.55; H, 6.69; N, 15.51. Found: C, 50.77; H, 6.71; N, 14.96.

Cyclopentylmethyl(pyridine)cobaloxime. Cyclopentylmethanol (Aldrich Chemical Co.), 2.0 g (20 mmol), was dissolved in 40 ml of ether in a 100-ml three-necked flask and cooled to about 0°. Dry N_2 was blown through the flask, and 20 mmol of methyllithium (9.4 ml of 2.13 *M* solution, Alfa) was slowly added. After addition was complete, the reaction mixture was allowed to stir for 5 min, and then 3.81 g (20 mmol) of solid *p*-toluenesulfonyl chloride was added under N_2 during a 10-min interval. The flask was stoppered and allowed to stir for 26 hr at 3°. After this time, the reaction mixture was shaken with 50 ml of water in a separatory funnel and the organic layer separated. Work-up by the normal procedure gave 3.5 g (71% yield) of the tosylate. Reaction of the tosylate with the cobaloxime(I) solution gave cyclopentylmethyl(pyridine)cobaloxime: NMR ($CDCl_3$) δ 0.6–2 (broad multiplets), 2.07 (singlet, Me of DMG), 7.0–8.6 (pyridine multiplets).

Anal. Calcd for $C_{19}H_{30}N_5O_4CO$: C, 50.55; H, 6.69; N, 15.51. Found: C, 50.85; H, 6.64; N, 15.10.

General Oxygen Insertion Reaction Procedure. These reactions can be run in a variety of organic solvents, $CHCl_3$, CH_2Cl_2, MeOH, and benzene for example. The preparative photolysis reactions were run in a round-bottomed flask sealed with a serum cap.

stirred magnetically, with either dry air or oxygen passing through the solution by means of syringe needles. Concentrations varied between 0.5 and 2 mmol of cobaloxime per 100 ml of solvent and, in general, were run at −10 to 0°. Photolysis was with 775 W of visible light (sun lamps) filtered through copper sulfate solution.[13] The reactions were run to complete conversion of starting material. At the end of the reaction, the solvent was stripped off at room temperature, and the crude dioxy product was purified by column chromatography (silica gel, elution with 1:1:1 MeOH–EtOAc–$CHCl_3$). The dioxy products obtained are reddish brown to black depending on the alkyl group.

For the two reactions studied with the 5-hexenyl(pyridine)cobaloxime in Table I, the specific conditions are as follows:

Experiment 1. 5-Hexenyl(pyridine)cobaloxime (1.2 g) was dissolved in 100 ml of reagent grade benzene in a glass tube sealed at one end, i.d. 25 mm. The solution was stirred magnetically and maintained at 35°. Air was slowly (about 2 mm/min) passed through a drying tube and then through benzene, and this saturated air was allowed to pass by the reaction mixture by means of a T tube. This allowed the reaction to be run under an air atmosphere at 35° with a minimum solvent evaporation. The photolysis was carried out with 1075 W (four lamps, about 6 in. away), filtered through copper sulfate, and allowed to proceed until all the starting material was reacted, about 41 hr. The benzene was stripped off at 35° and the crude material column chromatographed as above [5-hexenyldioxy(pyridine)- and cyclopentylmethyldioxy(pyridine)cobaloxime have identical R_f values].

Experiment 2. 5-Hexenyl(pyridine)cobaloxime (0.25 g) was dissolved in 25 ml of benzene in a test tube sealed with a serum cap. The photolysis conditions were identical with above except that benzene saturated oxygen was bubbled through the reaction solution at about 10 ml/min. The reaction was allowed to proceed to complete conversion of starting material, about 3 hr. Isolation and purification were as described in experiment 1.

Reduction of Dioxycobaloximes. 2-Butyldioxy(pyridine)cobaloxime, 1.32 g (2.88 mmol), was suspended at room temperature in 40 ml of dry diglyme in a 100-ml round-bottomed flask with vigorous stirring. Solid sodium borohydride was added in four 0.1-g portions. After stirring at room temperature for 0.5 hr, 2 ml of ethylene glycol was added in several portions. The reaction flask was then placed into a 110° oil bath and fitted with a small Vigreux distillation head, and a vacuum was applied. The 2-butanol distilled at 38° (69 mm). The pressure was lowered to 59 mm, and the diglyme began to distill at 88°. The first 5 ml of distillate was collected, and a 61% yield of 2-butanol was obtained pure by preparative GLC: QF-1 on firebrick, column 142°, injector 230°.

2-Hydroxy-1-phenethyldioxy(pyridine)cobaloxime, 0.85 g (1.63 mmol), was dissolved in 75 ml of dry THF, and this was slowly added by means of a dropping funnel to a mechanically stirred suspension of 0.3 g of $LiAlH_4$ in 50 ml of THF. The color of the cobaloxime solution changed from reddish brown to greenish brown and a precipitate formed. After all the cobaloxime was added, the mixture was allowed to stir for an additional hour, and then 5 ml of saturated aqueous NH_4Cl was added dropwise. The resulting mixture was filtered and dried with $MgSO_4$ and the THF stripped off leaving a yellow oil. This oil was dissolved in a small amount of ether and column chromatographed (silica gel, elution with ether) to give pure phenyl-1,2-ethanediol in 30% yield.

The dioxy product mixtures from experiments 1 and 2 in Table I were reduced with a large excess of sodium borohydride in triglyme (about 1 mmol of cobaloxime/50 ml of solvent). The reaction was carried out at room temperature for 21 hr. At the end of this time, the reaction mixture was subjected to vacuum distillation and the first 5 ml of distillate collected, bp 100–101° (8.5 mm). The distillate was analyzed on a Ucon oil 50HB2000 column (20% on 60–80 firebrick), column 170°, injector 212°. The distillate was also subjected to preparative GLC on a QF-1 column, the mixture of alcohols being collected and structures proved by NMR.

Other Experiments. All the experiments described in the section dealing with mechanism, except those previously described, were run in NMR tubes. Sufficient details are given in the text of the paper. The low temperature reactions were run using a silvered (except for a small clear space to allow light through for photolysis) vacuum jacketed glass apparatus, the temperature being achieved by a nitrogen flow splitter and a Dry Ice–2-propanol bath. All product composition analysis was done by NMR.

Acknowledgment. Financial support from the National Institutes of Health (GM-15373) is gratefully acknowledged.

References and Notes

(1) See F. R. Jensen and R. C. Kiskis, *J. Organomet. Chem.*, **49**, C46 (1973), for preliminary communication.
(2) National Science Foundation Predoctoral Fellow, 1970–1973.
(3) J. M. Pratt, *J. Chem. Soc.*, 5154 (1964).
(4) J. M. Pratt and B. R. D. Whitear, *J. Chem. Soc. A*, 252 (1971).
(5) J. H. Bayston, N. Kelso King, F. D. Looney, and M. E. Winfield, *J. Am. Chem. Soc.*, **91**, 2775 (1969).
(6) A. L. Crumbliss and F. Basolo, *J. Am. Chem. Soc.*, **92**, 55 (1970).
(7) B. M. Hoffman, D. L. Diemente, and F. Basolo, *J. Am. Chem. Soc.*, **92**, 61 (1970).
(8) G. Costa, G. Mestroni, and G. Pellizer, *J. Organomet. Chem.*, **15**, 187 (1968).
(9) G. N. Schrauzer and L. P. Lee, *J. Am. Chem. Soc.*, **92**, 1551 (1970).
(10) C. Fontaine, K. N. V. Duong, C. Merienne, A. Gaudemer, and C. Giannotti, *J. Organomet. Chem.*, **38**, 167 (1972).
(11) K. N. V. Duong, C. Fontaine, C. Giannotti, and A. Guademer, *Tetrahedron Lett.*, 1187 (1971).
(12) C. Giannotti, A. Gaudemer, and C. Fontaine, *Tetrahedron Lett.*, 3209 (1970).
(13) M. Kasha, *J. Opt. Soc. Am.*, **38**, 929 (1948).
(14) C. Giannotti, C. Fontaine, and A. Gaudemer, *J. Organomet. Chem.*, **39**, 381 (1972).
(15) Among the possibilities are an SH2 reaction on carbon, presumably needing the light source to activate the carbon–cobalt bond for those complexes with relatively strong bonds. Another possible mechanism has been proposed[16] involving the dissociation of one of the planar ligand nitrogens followed by coordination of oxygen at this site. Then a stereospecific cis migration of the alkyl group occurs followed by recoordination of the nitrogen.
(16) D. Dodd and M. D. Johnson, *J. Organomet. Chem.*, **52**, 1 (1973).
(17) G. N. Schrauzer, *Acc. Chem. Res.*, **1**, 97 (1968).
(18) (a) H. A. Lee and R. H. Abeles, *J. Biol. Chem.*, **238**, 2367 (1963); (b) B. Babior, *Fed. Proc., Fed. Am. Soc. Exp. Biol.*, **26**, 344 (1967); (c) H. G. Wood, R. W. Kellermeyer, R. Stjernholm, and S. H. G. Allen, *Ann. N.Y. Acad. Sci.*, **112**, 661 (1964); (d) H. A. Barker in, "The Bacteria", Vol. 2, I. C. Gunsalus and R. Y. Stanier, Ed., Academic Press, New York, N.Y., 1961.
(19) F. R. Jensen, V. Madan, and D. H. Buchanan, *J. Am. Chem. Soc.*, **93**, 5283 (1971).
(20) A. G. Davies and R. Feld, *J. Chem. Soc.*, 665 (1956).
(21) The instrument manual specifies that meaningful rotation can be obtained with as little as 10% transmittance at 589 nm. Racemic 2-hydroxy-1-phenethyl(pyridine)cobaloxime gave no rotation at the same concentration so the rotation seen with the optically active compound is real.
(22) F. R. Jensen and R. C. Kiskis, unpublished results.
(23) M. Julia, *Acc. Chem. Res.*, **4**, 386 (1971).
(24) C. Walling and A. Cioffari, *J. Am. Chem. Soc.*, **92**, 6609 (1970).
(25) J. F. Garst, P. W. Ayers, and R. C. Lamb, *J. Am. Chem. Soc.*, **88**, 4260 (1966).
(26) J. K. Kochi and J. W. Powers, *J. Am. Chem. Soc.*, **92**, 137 (1970).
(27) A previous attempt to observe cyclization in this system was not successful: C. Merienne, C. Giannotti, and A. Gaudemer, *J. Organomet. Chem.*, **54**, 281 (1973).
(28) A similar product could be formed from a carbanion; however, the -OH groups in the planar ligand system readily react with strong bases and would be expected to intercept the intermediate to form an alkane. In view of the good isolated product yields, it is highly unlikely that a carbanion is involved in the reaction.
(29) Note that both reactions were carried out at 35°, and the effect of temperature on cyclization was not studied. In that under our conditions lowering the temperature would increase the solubility of oxygen, a decrease in relative amount of cyclization would have been seen but could not be assigned unequivocally to a pure temperature effect. A more detailed study would have to be undertaken.
(30) G. N. Schrauzer and R. J. Windgassen, *J. Am. Chem. Soc.*, **88**, 3738 (1966).
(31) G. N. Schrauzer, L. P. Lee, and J. W. Sibert, *J. Am. Chem. Soc.*, **92**, 2997 (1970).
(31) (a) The referees have noted to us the paper by Gaudemer and coworkers [K. N. V. Duong, A. Ahond, C. Merienne, and A. Gaudemer, *J. Organomet. Chem.*, **55**, 375 (1973)] in which was reported the results of photolysis of 5-hexenylcobaloxime under anaerobic conditions in a nonspecified solvent. (Phenylacetylene may have also been present.) Analysis was carried out by examination of the volatiles by NMR spectroscopy. Methylcyclopentane was reported to be absent, and 1,5-hexadiene was said to be uniquely obtained (actual yield not specified), and it was concluded no free alkyl radicals were formed. No comment was made regarding the presence or absence of methylenecyclopentane, the product expected from radical cyclization and (radical induced) β elimination, the reaction under study. Aside from additives, the principally known difference in experimental conditions was temperature (present work 35 vs 0 to −20° by Gaudemer and coworkers). However, reconcilliation of the results will require further work.
(32) C. Giannotti, B. Septe, and D. Benlian, *J. Organomet. Chem.*, **39**, C5 (1972).
(33) C. Giannotti and B. Septe, *J. Organomet. Chem.*, **52**, C45 (1973).

(34) C. Giannotti and B. Septe, *J. Organomet. Chem.*, **52**, C36 (1973).
(35) Paths B and H may occur concertedly without the intervention of the hypothetical vibrationally excited intermediate X. In solution, relaxation of such intermediates is generally regarded as occurring faster than chemical reaction. The state X is included to provide an overview of reaction pathways and because the role, if any, of such vibrationally excited intermediates in very complex molecules, such as cobaloximes, cannot be assessed at the present time. Similar considerations hold for paths D and E and the vibrationally excited intermediate XI.
(36) A detailed study of the kinetics and mechanism of the replacement of pyridine by tri-*n*-butylphosphine has been made and demonstrates conclusively that the mechanism is a pure dissociative process proceeding through the base-off complex: F. R. Jensen and R. C. Kiskis, *J. Am. Chem. Soc.*, preceding paper in this issue.
(37) Extinction coefficients for λ_{max} in the charge transfer region for several alkylcobaloximes with bases varying from very weakly to very strongly coordinating are given in ref 31. They vary only about a factor of 2 having 1.5×10^3 as about the maximum for the simple alkyl cobaloximes.
(38) Support for this line of reasoning comes from ref 31, where photolysis rate constants cleanly first-order in cobaloxime were obtained under conditions essentially identical with those reported in the present work.
(39) The mechanism through path D does not specifically require this reversibility in that base exchange can occur through path E before homolysis occurs.
(40) G. N. Schrauzer, *Inorg. Synth.*, **11**, 61 (1968).
(41) E. L. Eliel and D. W. Delmonte, *J. Org. Chem.*, **21**, 596 (1956).
(42) L. F. Fieser and M. Fieser, "Reagents for Organic Synthesis", Vol. 1, Wiley, New York, N.Y., 1967, p 1180.

Solvent Effects in the Kinetics of Electron Transfer between *N*-*n*-Butyl-phthalimide Radical Ion and Its Parent Molecule

Y. Shimozato, K. Shimada, and M. Szwarc*

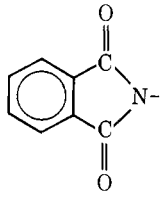
Contribution from the Department of Chemistry, State University of New York College of Environmental Science and Forestry, Syracuse, New York 13210.
Received March 10, 1975

Abstract: The bimolecular rate constants, k_{ex}, of electron transfer between radical anions of *N*-*n*-butyl-phthalimide and its parent compound (BuPI) were determined in five solvents over temperatures ranging from −40 to +45°. The rate of exchange was derived by matching the experimental ESR spectra with those simulated by computer. The experimental and the computer-simulated spectra are extremely sensitive to minute variations in the coupling constants which therefore have to be determined with a high degree of accuracy.

Our previous studies[1,2] of *intra*molecular electron exchange between two aromatic end groups linked by molecular chains were extended recently to compounds having the structure

$$\text{PI-(CH}_2)_n\text{-PI or PI-(CH}_2\text{CH}_2\text{O)}_i\text{-CH}_2\text{CH}_2\text{-PI}$$

where PI denotes the phthalimide moiety



Evaluation of the results of that work, reported in the following paper,[3] calls for analysis of the ESR spectra of *N*-butylphthalimide (BuPI) radical anions in a variety of solvents and for determination of the bimolecular rate constants of exchange

$$\text{BuPI}\cdot^- + \text{BuPI} \overset{k_{ex}}{\rightleftarrows} \text{BuPI} + \text{BuPI}\cdot^-$$

measured in those solvents over a wide range of temperatures. Our findings are summarized in this paper.

Coupling Constants of Bu-PI·⁻

The ESR spectrum of BuPI·⁻ radical anions was reported by Hirayama[4] and that of the closely related ethyl derivative was studied by Nelsen[5] as well as by Hirayama.[4] Our results are listed in Table I. Solvents affect the values of the coupling constants only slightly; nevertheless, these small changes strongly modify the shape of the recorded spectrum as illustrated by Figure 1. For the same reason, the shape of the computer-simulated spectrum of BuPI·⁻ in acetonitrile deviates appreciably from the recorded one when Hirayama's coupling constants are adopted in the simulation. However, their slight alterations, shown in the last column of Table I, yield a simulated spectrum that fully resembles the experimental one. Therefore, it has been imperative to obtain highly accurate coupling constants to ensure the reliability of the results discussed in the following paper. The constants listed in Table I are reliable within ±0.05 G.

Kinetics of Exchange: BuPI·⁻ + BuPI → BuPI + BuPI·⁻

The bimolecular rate constants, k_{ex}, of this exchange reaction have been determined by the method outlined by Norris.[6] The BuPI·⁻ radical ions were dissolved in the chosen solvent together with the required amounts of the parent compound and their ESR spectra recorded at various temperatures. The recorded spectra were matched then with the computer-simulated ones.

The computer-drawn spectra were simulated for various lifetimes, τ of the radicals, using the coupling constants listed in Table I. The results were virtually identical whether the $1/T_2$ value fed into the computer was 30 or 60 mG, provided $1/\tau \geq 0.2$ G. For $1/\tau < 0.2$ G, it was necessary to assume $1/T_2 = 60$ mG in order to simulate the shape of the experimental spectrum observed in the absence of exchange. This is caused by the incapability of our spectrometer to resolve lines narrower than 60 mG. Consequently, the value $1/T_2 = 60$ mG was adopted in all our computations.

For the sake of illustration, the recorded spectra of the radicals dissolved in HMPA in the presence of 1.5×10^{-2} *M* of the phthalimide are shown in Figure 2 together with