1981

Kinetic studies of organocobalt compounds related to vitamin B12 coenzymes

Helen Broom Gjerde
Iowa State University

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KINETIC STUDIES OF ORGANOCOBALT COMPOUNDS RELATED TO VITAMIN B-12 COENZYMES

Iowa State University PH.D. 1981

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Kinetic studies of organocobalt compounds related to vitamin B_{12} coenzymes

by

Helen Broom Gjerde

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GENERAL INTRODUCTION

The kinetic and mechanistic studies outlined in this dissertation pertain to the reactions of two distinct organocobalt complexes. The mode of decomposition and the products of decay of the unstable alkylcobaloxime, α-phenylethyl(aquo)cobaloxime, are the subjects of Part I. The cobalt complex examined in Part II is vitamin B_{12s}, a cobalt(I) corrin complex, also known as cob(I)alamin. Its reactivity as a strong one-electron reducing agent toward $Cr(H_2O)_5X^{2+}$ species is demonstrated.

The balance of this Introduction includes a summary of selected aspects of the structures and reactions of vitamin B_{12s} derivatives- ("cobalamins") and bis(dimethylglyoximato)cobalt complexes- (cobaloximes"). Material more directly pertinent to the individual studies is given in the introductions to Parts I and II.

Beginning with the isolation of vitamin B_{12} in 1948, the chemistry of the B_{12} coenzyme has been expanded from the elucidation of its X-ray crystal structure to analyzing the mode of cobalt-carbon bond cleavage (1). Vitamin B_{12} is unique in that it is the only naturally occurring transition metal organometallic compound to be recognized, and is one of the most stable organocobalt complexes ever reported. The coenzyme was originally isolated as the cyanocobalt derivative or cyanocobalamin (Figure I-1). When it was later discovered that the actual cobalt organoligand is 5'-deoxyadenosyl (2), interest was sparked in synthetic work for the preparation of alkylcobalamins and in the coordination chemistry of cobalamins in general.

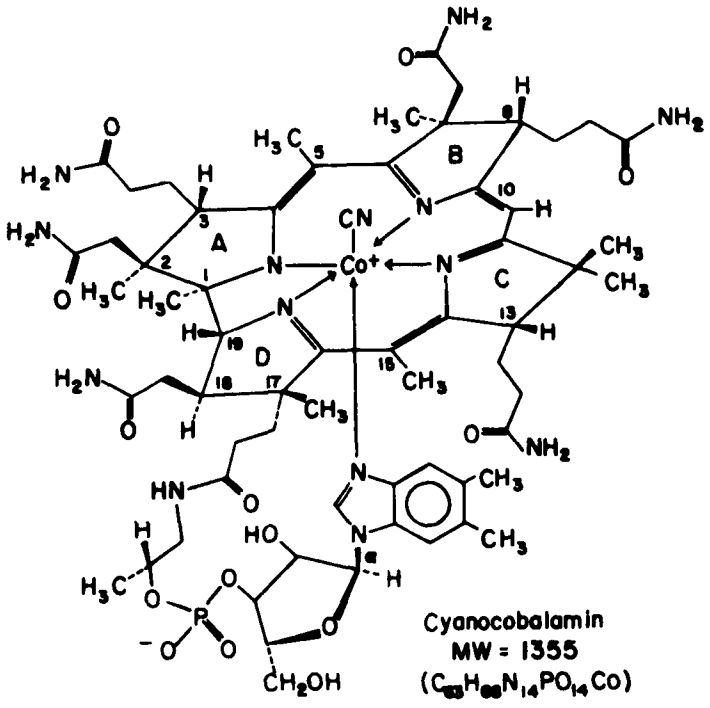


Figure I-1. Molecular structure of vitamin B_{12}. The positive charges of the cobalt(III) ion are balanced by the negative charges on the corrin ring, the cyanide, and the phosphate

The CH_3-Co derivative, methylcobalamin, was actually isolated from Clostridium thermoacetium which synthesize acetate from glucose and CO_2 (3). It also plays a part in the in vivo synthesis of methionine from homocysteine (4) and the formation of methane by Methanosarcina barkeri (5).

In view of these important biological functions of the alkylcobalamins, it is highly desirable to have simple model compounds available which may be prepared in large quantity and can be used to test the mechanistic interpretations derived from the biochemical experiments. Bis(dimethylglyoximato)cobalt complexes reproduce the basic metal reactions of cobalamins and are excellently suited for the study of the mechanisms of vitamin B_{12} catalyzed processes (6-9). Figure I-2 shows the similarity in structure between cobalamins, or vitamin B_{12} coenzymes, and bis(dimethylglyoximato)cobalt complexes. For convenience and because of their resemblance to cobalamins, bis(dimethylglyoximato)cobalt complexes are called "cobaloximes." The tendency of the organoligands to stabilize the Co-C σ bond in cobalamins and cobaloximes is independent of the detailed nature of the vertical π-electron system. All that is required is the presence of a cobalt ion in a sufficiently strong, essentially planar ligand field. Because the dimethylglyoxime moiety imposes less steric restrictions than the corrin ligand, the stability of cobaloximes is usually greater than that of the corresponding cobalamins. Alkylcobalamins can be regarded in a formal sense as complexes of cobalt(III) with a carbanion, and alkylcobaloximes are similarly constituted. Their reactions,

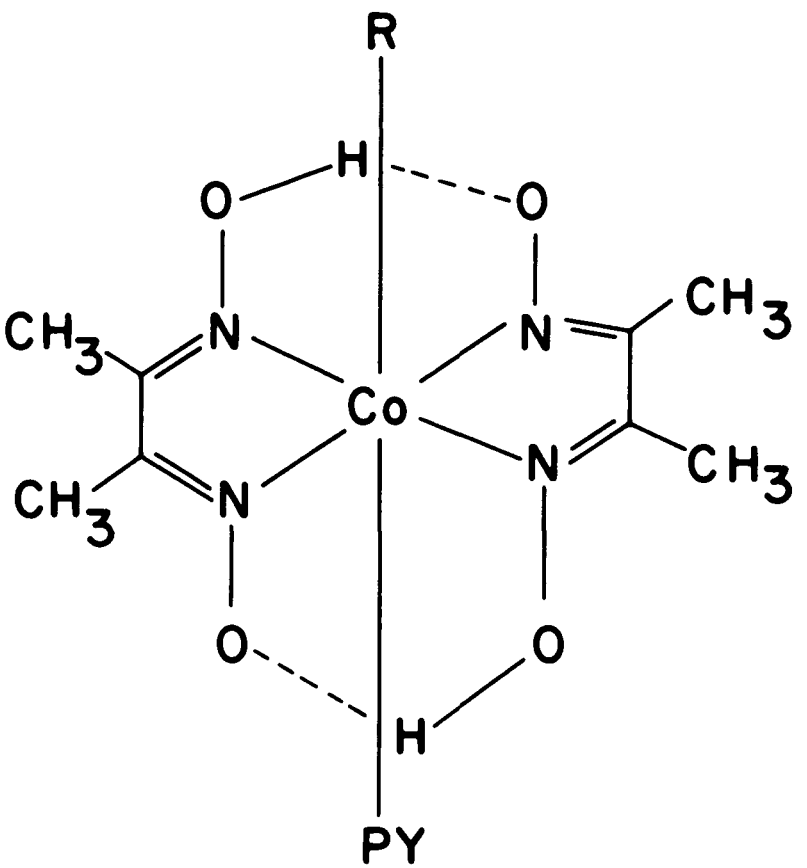


Figure I-2. Molecular structure of an organocobaloxime, where R = alkyl or aryl group

however, may include processes in which the Co-C bond undergoes homolytic scission resulting in production of the cobalt(II) complex and a free radical.

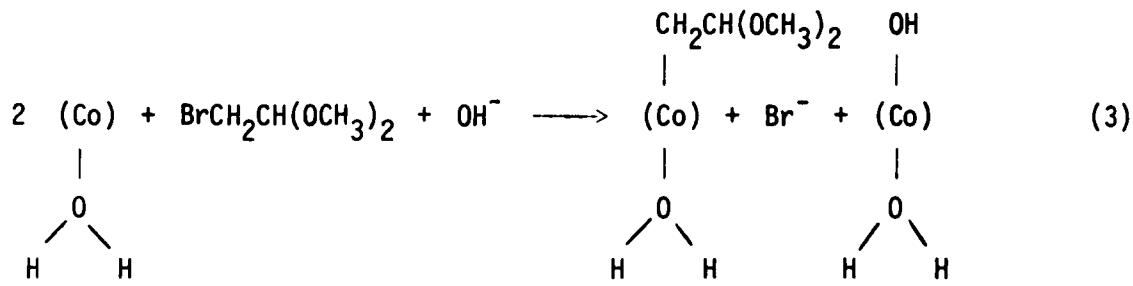
Whereas simple alkylcobaloximes are unusually stable, variation of the reactivity of the Co-C bond results on introduction of substituents to the cobalt-bound alkyl group. For instance, methyl- or ethylcobaloximes are very stable toward acids or bases; β-hydroxyethylcobaloxime, on the other hand, readily decomposes both in mildly acidic or basic media as shown in Equation 1 (10).

$$\begin{aligned} HOCH_2CH_2Co(dmgH)_2(OH_2) &\xrightarrow{H^+} (H_2O)_2Co(dmgH)_2^+ + C_2H_4 \\ &\xrightarrow{OH^-} Co(dmgH)_2^- + CH_3CHO + 2H_2O \end{aligned} \qquad (1)$$

Substituted alkylcobaloximes may be prepared from bis(dimethylglyoximato)cobalt(I) and alkyl halide derivatives in basic solution (Equation 2):

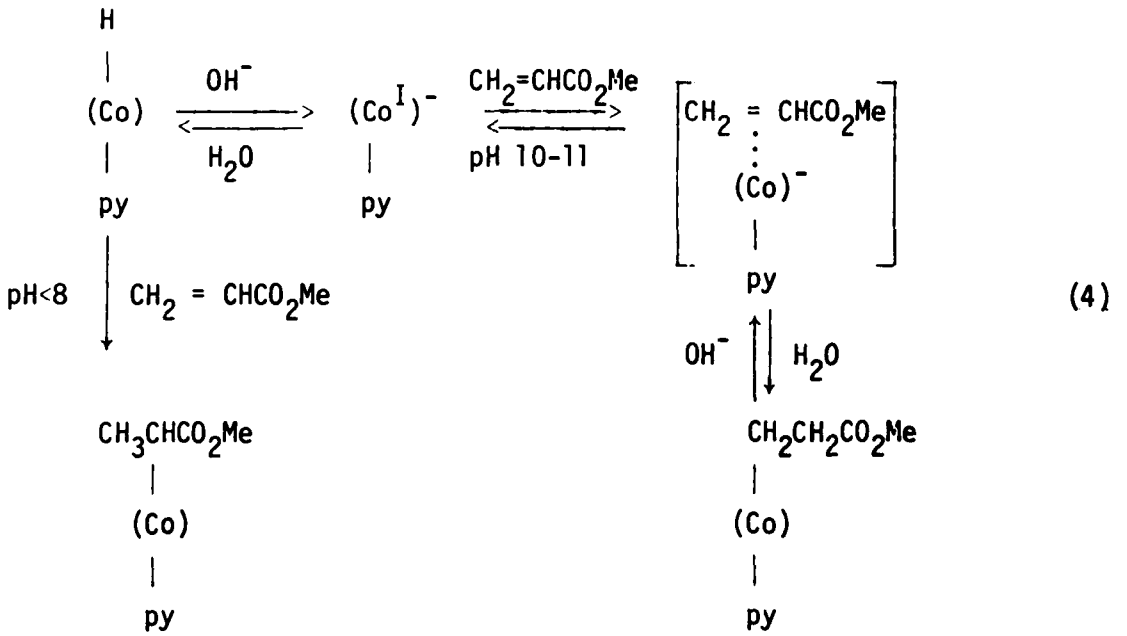
$$\begin{array}{l} (Co^I)^- \\ \quad | \\ \quad py \end{array} + ClCH_2CN \longrightarrow \begin{array}{l} CH_2CN \\ | \\ (Co) \\ | \\ py \end{array} + Cl^- \qquad (2)$$

They may also be synthesized from bis(dimethylglyoximato)cobalt(III) and alkyl halides (Equation 3):



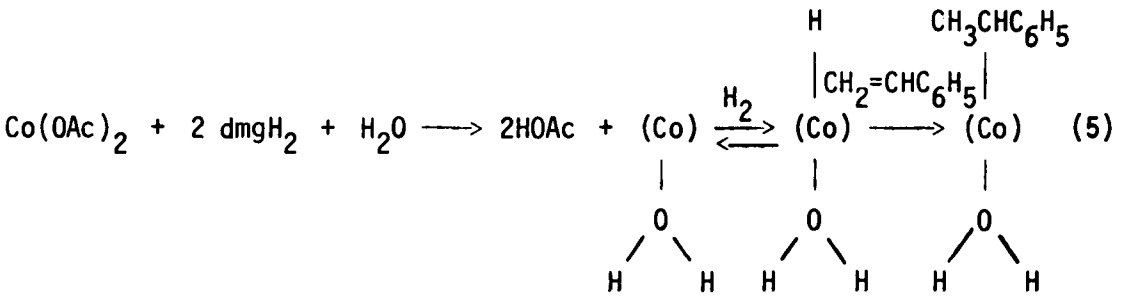
(3)

Substituted olefins react with reduced cobaloximes in both acidic and basic solutions to form the expected alkylcobaloximes. Under alkaline conditions, only electronegatively substituted olefins react with the nucleophilic cobalt atom, to produce β-substituted ethylcobaloximes (6). A significant change in the mode of addition of the cobalt species to the double bond takes place in neutral or only slightly alkaline solution. Here the α-substituted alkylcobaloxime is formed exclusively (10). An example of this is given for the synthesis of α- and β-carbomethoxyethylcobaloximes (Equation 4):



(4)

For the synthesis of the α-substituted organocobaloximes, it is preferable to stir together cobalt(II) acetate, dimethylglyoxime, and a solution of the olefinic substrate under 1 atm of hydrogen as shown in Equation 5.



In neutral solution, hydridocobaloxime transfers the axial hydrogen to the β- carbon atom of the substituted olefin. In alkaline solution, the reduced cobaloxime is essentially present as the strongly nucleophilic anion $(Co^{I})^{-}$. The normal nucleophilic addition to the olefin is believed to take place via an initial π complex formed between the olefinic double bond and the cobalt moiety.

An exception to this pH dependence on the mode of addition is found in the synthesis of α-phenylethylcobaloxime, $C_6H_5CH(CH_3)(Co)py$ The reaction product of styrene with cobaloxime(I) in basic solution is not the β- but rather the α-phenylethylcobaloxime derivative; it is formed both under alkaline and neutral conditions. Vitamin B_{12s}, or cobalt(I) B_{12s} coenzyme, was reported not to react with styrene (11). This may be due to steric effects, which would favor the formation of the β isomer. Because the β isomer could not be obtained from styrene even with the cobaloximes, it is not surprising that it does not form

with the corresponding cobalamin species. The β isomer can be obtained only from the reaction of β-bromoethylbenzene and $Co^{I}(dmgH)_2py$, via the reaction of Equation 2 (12). Once formed, it shows the high thermal stability associated with simple alkyls.

The thermal decomposition of simple alkylcobaloximes leads to cleavage of the Co-C bond (8). The products of the cleavage are unrearranged paraffins and olefins, olefins being formed only when a β-hydrogen is present (8). The results are consistent with cobalt-carbon bond homolysis followed by polymerization and hydrogen abstraction reactions. The decomposition of substituted alkylcobaloximes appears to depend on electronic as well as steric factors. Cobaloximes with bulky alkyl groups attached to the cobalt are thermally less stable. Particularly striking is the difference in thermal stability between α- and β-phenylethyl(py)cobaloximes. The α isomer decomposes around 90°, the β compound around 175°C (10). Both saturated and unsaturated products are isolated from the decomposition of the substituted α- and β-ethylcobaloximes, and the ratio of olefin: polymer can vary considerably from one cobaloxime to another for reasons which may be different in each individual case. The photolytic behavior of substituted alkylcobaloximes parallels the results of the thermal decomposition.

The introduction of an electronegative substituent in the α position of an alkylcobaloxime has little effect on the gross chemical properties except that reductive cleavage of the Co-C bond occurs more readily. Carboxymethylcobaloxime has a pK_a of 7.14 (25°C), and it has

been shown that attachment to cobalt does not facilitate decarboxylation (10). Thermal decomposition produces esters of acetic acid as the main product of Co-C bond cleavage; the cobaloxime with free acid yields acetic acid and only very little methane and CO_2 (13).

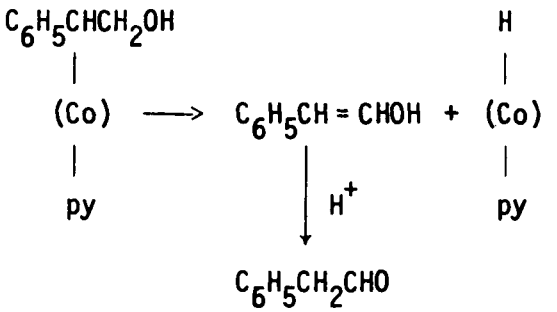
Electronegative substituents in the β position of ethylcobaloximes introduce alkali sensitivity caused by the type of elimination shown in Equation 6 (10).

$$\begin{array}{l} CH_2CH(R)X \\ | \\ (Co) \\ | \\ py \end{array} + OH^- \rightleftharpoons (Co^I)^- + CH_2 = C(R)X + H_2O \qquad (6)$$

The β-substituted alkylcobaloximes undergo an unusual rearrangement into the α compounds in basic solutions. The rearrangement appears to involve the formation of a labile π-bonded intermediate. Isomerization of β-substituted alkylcobalamin derivatives has been suggested to be involved in the methylmalonyl-succinyl-CoA and the glutamic-methyl-aspartic mutase enzymes (5).

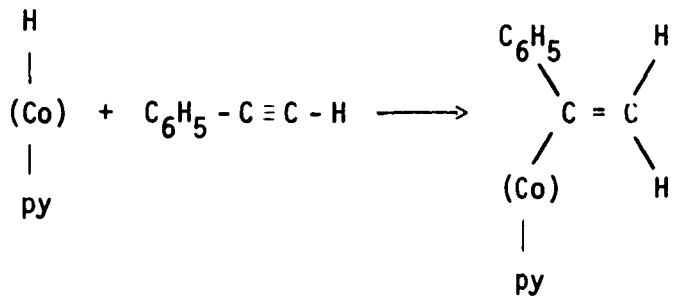
PART I. DECOMPOSITION OF α-PHENYLETHYL(AQUO)COBALOXIME

It had been shown earlier (15) that the primary products of thermolysis of $C_6H_5CH(CH_2OH)(Co)py$ in methanol solution at 40°C consisted of hydrido(py)cobaloxime and the enol of phenylacetaldehyde, $C_6H_5CH{=}CHOH$, which is rapidly transformed into the aldehyde by acid catalysis. Phenylacetaldehyde was isolated as a solid (Equation 7).



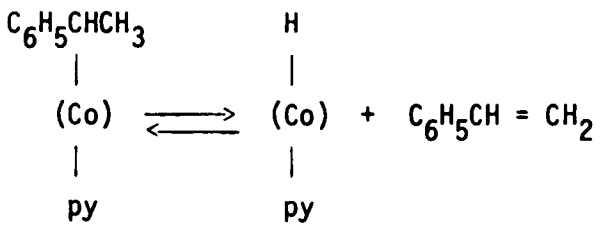
(7)

The highly reactive hydrido(py)cobaloxime in the product mixture was detected by its reaction with phenylacetylene to form α-styryl(py)-cobaloxime (Equation 8).



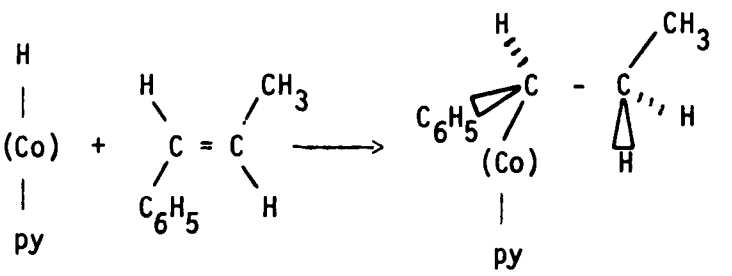
(8)

It was postulated that reaction 7 is a general one for alkylcobaloximes possessing a hydrogen on the β-carbon, and that the same reaction occurs under photochemical as well as thermal conditions. This study was extended to the anaerobic thermolysis of α-phenylethyl-(py)cobaloxime in acetone or chloroform as shown in Equation 9.



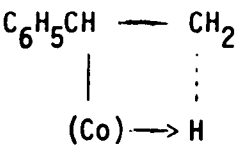
(9)

Hydrido(py)cobaloxime was scavenged from the reaction mixture with trans-phenylpropene (Equation 10).



(10)

Deuterium labelling showed that the product results from cis addition of D(Co)py across the ethylenic double bond (16). As a consequence of this study, these workers concluded that it is unnecessary to propose homolytic cleavage of the Co-C bond during the course of thermolysis or photolysis. The β-elimination process which would lead to the observed products was postulated to occur by a four-centered concerted mechanism.



The second study of the decomposition of α-phenylethyl(py)-cobaloxime was reported six years later by Halpern et al. (17). They postulated that decomposition of α-phenylethyl(py)cobaloxime in

toluene under a constant partial pressure of H_2 attained a measurable equilibrium according to Equation 11.

$$\begin{array}{l} C_6H_5CHCH_3 \\ \quad | \\ (Co) \quad \rightleftharpoons \quad (Co^{II}) \\ \quad | \qquad\qquad\quad | \\ \quad py \qquad\qquad py \end{array} + C_6H_5CH = CH_2 + 1/2\ H_2 \qquad (11)$$

The decay of the organocobaloxime followed a first-order rate law, and kinetic measurements yielded $k(25°C) = 7.8 \times 10^{-4}\ s^{-1}$; $\Delta H^{\ddagger} = 21.2 \pm 0.5$ kcal/mole; $\Delta S^{\ddagger} = -1.4 \pm 1.5$ cal/(mole degree) (Equation 12).

$$\frac{-d[C_6H_5CH(CH_3)(Co)(py)]}{dt} = k[C_6H_5CH(CH_3)(Co)(py)] \qquad (12)$$

Halpern et al. interpreted the kinetic results to mean that the rate-determining step of the decomposition reaction is homolytic cleavage of the cobalt-alkyl bond as postulated in Equations 13-15.

$$[C_6H_5CH(CH_3)(Co)(py)] \xrightarrow{k} \{[(Co^{II})(py)] + C_6H_5\dot{C}HCH_3\} \qquad (13)$$

$$\{[(Co^{II})(py)] + C_6H_5\dot{C}HCH_3\} \xrightarrow{fast} [H(Co)(py)] + C_6H_5CH = CH_2 \qquad (14)$$

$$[H(Co)(py)] \xrightarrow{fast} [(Co^{II})(py)] + 1/2\ H_2 \qquad (15)$$

The products of this reaction, hydrido(py)cobaloxime and styrene, are identical to those reported by Duong, Ahond, Merienne and Gaudemer (16); however, Halpern claims that hydrido(py)cobaloxime is rapidly converted

to $Co^{II}(dmgH)_2(py)$ and H_2. The rate of conversion of hydrido(py)-cobaloxime to $Co^{II}(dmgH)_2(py)$ and H_2 as a function of perchloric acid concentration in methanol-water solutions (18) would imply that the reaction in neutral solution is slow. The fact that Halpern and coworkers carried out their experiments in toluene, rather than methanol-water, may account for this apparent inconsistency.

The value obtained for the entropy of activation, -1.4 ± 1.5 cal/(mole degree), is unusual for a reaction whose rate-limiting step is homolysis. A large positive $\Delta S^{\ddagger}$ would be expected based on the usual thermodynamic considerations.

The opposite conclusions reached by these two research groups concerning the mode of decomposition of α-phenylethylcobaloxime provided an incentive to approach the problem from a different perspective. By altering the conditions of the reaction, that is, introducing acid and/or oxidant into the system, the product distribution is changed. Based on the analysis of such results, it is concluded that a certain percentage of α-phenylethylcobaloxime undergoes homolytic cobalt-carbon bond cleavage and that the balance decomposes by β-elimination. The complexity of this system may be characteristic of many α-substituted alkylcobaloximes, and a complete analysis of α-phenylethylcobaloxime could serve as a model for its analogues.

EXPERIMENTAL

Materials

$C_6H_5CH(CH_3)Co(dmgH)_2(py)$

α-Phenylethyl(py)cobaloxime was prepared according to the procedure of Schrauzer and Windgassen (10). Dimethylglyoxime ($dmgH_2$) (23.2 g, 0.2 mole) was stirred in 375 mL methanol under a strong flow of N_2. Upon addition of cobalt acetate (25 g, 0.1 mole), $Co(dmgH)_2 \cdot 2H_2O$ was formed, and the solution became dark brown. Styrene (15 mL, 0.25 mole) was syringed into the reaction mixture, and H_2 was continuously bubbled through the solution for 3-4 hours. In air, the dark brown solution was rapidly filtered, diluted with 25 mL water, and stirred. Pyridine (8 mL, 0.1 mole) was added, and an orange solid crystallized and was collected by filtration, washed with water, and air-dried. The desired product was recrystallized from CH_2Cl_2 and hexanes in approximately 30% yield.

$C_6H_5CH(CH_3)Co(dmgH)_2(H_2O)$

α-Phenylethyl(aquo)cobaloxime was prepared analogously to the pyridine adduct. Two milliliters of water was added to 375 mL methanol and 23.2 g (0.2 mole) $dmgH_2$ in a 500 mL three-necked round bottom flask. The solution was stirred and deaerated for one hour under N_2. After 25.0 g (0.1 mole) cobalt acetate and 14.0 mL (0.25 mole) styrene had been added, H_2 was bubbled through the solution for 3-4 hours. After this time, the solution was filtered under N_2 through a deaerated

filter stick into a round bottom receiving flask. The solvent was rotary evaporated at 30°C, and red crystals precipitated. The crystals were filtered in air and washed repeatedly with cold water, followed by hexanes. The resulting compound was air dried.

Miscellaneous reagents

$[Co(en)_3](ClO_4)_3$ Tris(ethylenediamine)cobalt(III) perchlorate was prepared by addition of 70% $HClO_4$ to an aqueous solution of tris-(ethylenediamine)cobalt(III) chloride (19). Crystallization occurred upon cooling, and the orange needles were filtered and washed with ethanol and diethyl ether.

$[Co(NH_3)_5Br](ClO_4)_2$ and $[Co(NH_3)_5Cl](ClO_4)_2$ The perchlorate salts were obtained from the corresponding bromide and chloride compounds by dissolution in water, adding 70% $HClO_4$, and cooling in ice (20 and references therein).

Styrene Reagent grade (Aldrich) and was used as purchased.

H_2O_2 Reagent grade, 30% H_2O_2 (Fisher), was used as purchased, its molarity determined by reaction with excess iodide ion followed by thiosulfate titration of the liberated iodine.

$Cu(ClO_4)_2$ Aqueous solutions were prepared by dissolving the solid (G. F. Smith) in dilute $HClO_4$. Standardization was done iodometrically.

$Fe(ClO_4)_3$ Aqueous solutions of iron(III) perchlorate in $HClO_4$ were made and analyzed by published procedures (21).

$Cr(ClO_4)_2$ Aqueous solutions were prepared from chromium(III) perchlorate in dilute acid by reduction over amalgamated zinc under a nitrogen atmosphere.

Gases Nitrogen and hydrogen (Air Products) were purified of traces of O_2 by passage through two Cr^{2+}_{aq} scrubbing towers and distilled water.

$HClO_4$ and $LiClO_4$ Aqueous solutions of perchloric acid were made by dilution of 70% $HClO_4$ and titrated with standardized NaOH to a phenolphthalein end point. $LiClO_4$ was prepared by addition of 70% $HClO_4$ to an aqueous slurry of the carbonate, until no more CO_2 was evolved. The solution was evaporated until crystals of $LiClO_4$ formed, which were collected and recrystallized from water until no longer acidic. An aqueous solution was analyzed for the molarity of Li^+ by addition of an aliquot to a Dowex 50W - X8 cation exchange column in the H^+ form, and titrating the displaced acid with NaOH.

Methods

Analyses and characterization

$C_6H_5CH(CH_3)Co(dmgH)_2(py)$ Anal. Calcd. for $CoC_{21}H_{28}N_5O_4$: Co, 12.42; C, 53.17; H, 5.95; N, 14.76. Found: Co, 12.39; C, 51.65; H, 6.00; N, 14.69. In a deoxygenated methanol/water mixture, the UV-visible spectrum of α-phenylethyl(py)cobaloxime showed absorption maxima at 464 nm (850 cm^{-1} M^{-1}) and 368 nm (3.02×10^3 cm^{-1} M^{-1}). A deoxygenated solution in $CDCl_3$ gave the following ^1H NMR spectrum: δ 0.60 (d, H3), 1.95 (s, H12), 3.50 (m, H1), 7.17 (m, H5), 7.30-7.40

(m, H5). The reported chemical shifts are (22): δ 0.63 (d, H3), 1.94 (s, H12), 3.54 (m, H1), 7.10 (m, H5), 7.20, 7.68-8.30 (m, H5).

$C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ The aquo derivative was analyzed quantitatively for cobalt by the cobalt thiocyanate spectrophotometric technique and found to contain 14.31% cobalt; the theoretical amount is 14.22%. The UV-visible spectrum shown in Figure I-3 is consistent with the structure assigned to the organocobaloxime. The molar absorptivities for α-phenylethyl(aquo)cobaloxime in 40% v/v methanol/water solution were calculated for wavelengths of maxima absorbance to be (λ/nm (ε/cm^{-1} M^{-1})): 470 (1.40×10^3) and 368 (3.67×10^3). Aside from the pyridine resonances, the ^1H NMR spectrum of α-phenylethyl-(aquo)cobaloxime is identical to that of the pyridine adduct.

Inorganic product analysis

The most successful method found to analyze for Co_{aq}^{2+}, produced from the decomposition of α-phenylethyl(aquo)cobaloxime in acid, was addition of 50% NH_4SCN to an acidic portion of the product solution, followed by 25 mL of acetone. The solution was diluted to 50 mL with distilled water. The amount of NH_4SCN added is crucial to the development of the $Co(NCS)_4^{2-}$ complex ion; otherwise, green or yellow solutions result, rather than blue ones. Satisfactory blue solutions were obtained when 5 mL 50% NH_4SCN was added to 5 mL of the product solution. Absorbance readings were measured at 623 nm (1842 cm^{-1} M^{-1}). A linear calibration curve was obtained for this method when $CoCl_2 \cdot 6H_2O$ was used as a standard (23).

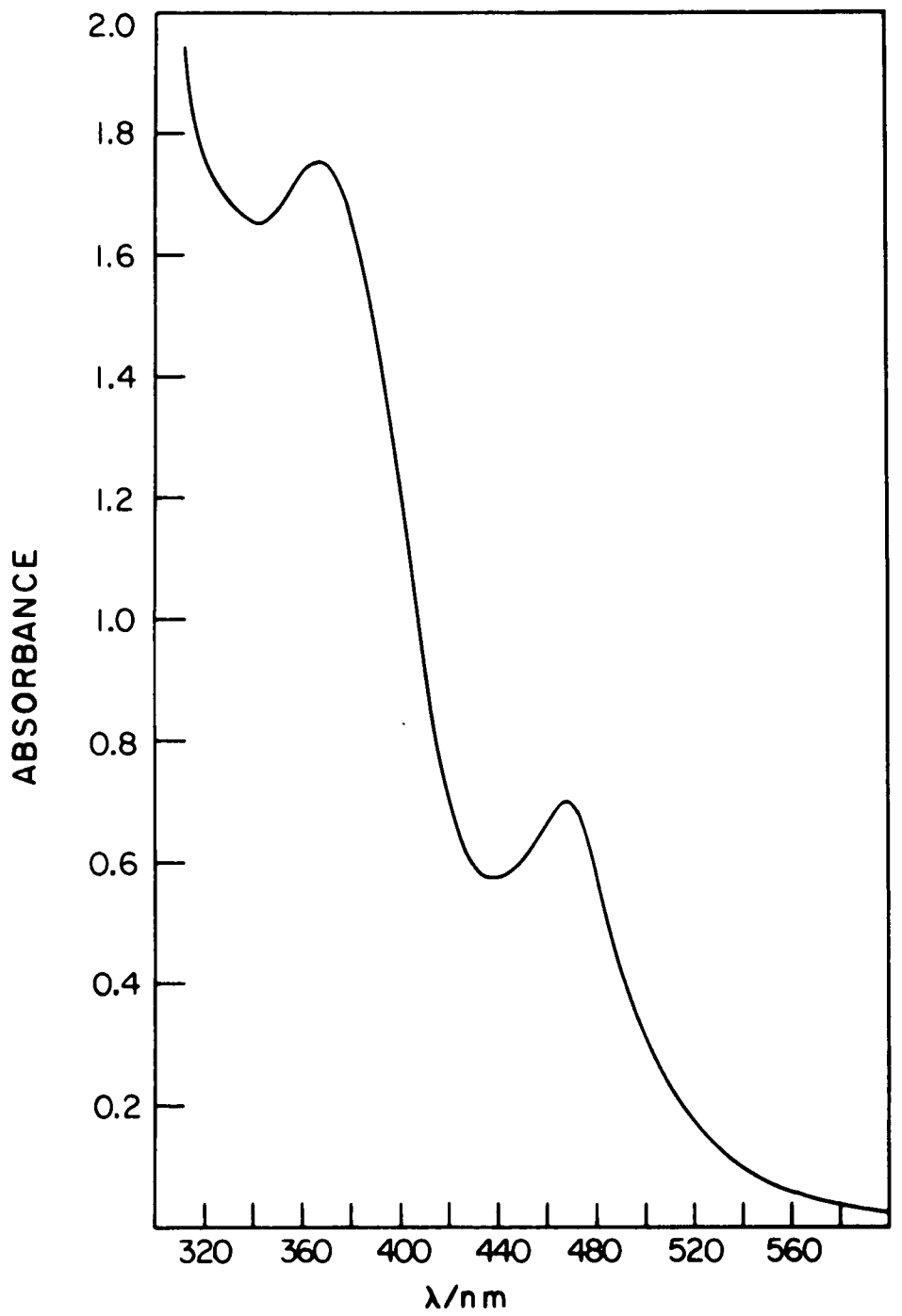


Figure I-3. The electronic spectrum of α-phenylethyl(aquo)cobaloxime. Concentration = 4.74×10^{-4} M; cell length = 1.00 cm

To test the total amount of cobalt present, 6.0 mL of the product solution was digested in a few milliliters of 70% $HClO_4$ almost to dryness. The difference between the total cobalt present in the sample and the Co_{aq}^{2+} produced yielded the amount of $(Co(dmgH)_2(H_2O)_2)^+$ formed in the reaction mixture.

Photochemically, Co_{aq}^{2+} could be generated from an acidic solution of α-phenylethyl(aquo)cobaloxime using a Rayonet photochemical reactor. The organocobaloxime was dissolved in deaerated 40% v/v methanol/water in a stoppered Pyrex vial. To this was added acid, and the solution was photolyzed for 30 minutes. Within this time, decomposition was complete, and 4.0 mL of the solution was transferred to a 50 mL volumetric flask for Co_{aq}^{2+} analysis. When photolysis was carried out in the presence of $Co(en)_3^{3+}$, no decomposition of the latter occurred. The absorption of $Co(en)_3^{3+}$ at 623 nm (6.8 cm^{-1} M^{-1}) was taken into account in deriving the amount of Co^{2+} produced from the cobaloxime.

Organic product analysis

The organic products from the decomposition of α-phenylethyl-(aquo)cobaloxime in acidic solution were analyzed by GC-MS methods. A sample was prepared by reacting 30-40 mg of accurately weighed α-phenylethyl(aquo)cobaloxime with 1 M $HClO_4$ in deaerated 40% v/v methanol/water solution. After completion of the reaction, dimethylglyoxime was filtered, and the organic products were extracted into CH_2Cl_2. The organic phase was concentrated to approximately 5 mL, syringed into a 10 mL volumetric flask, and diluted to volume with CH_2Cl_2.

Gas chromatographic separation of the dimeric products was carried out on a Tracor 550 instrument equipped with an OV-1 packed column with a FID detector at 150°C. An internal standard, bibenzyl, was used for quantitative analysis. Exact mass values of the dimeric compounds were obtained from samples which had been concentrated to dryness after extraction into CH_2Cl_2. A paste was formed which was appropriate for mass spectral analysis.

Styrene was quantitatively analyzed by the method of standard addition using the Tracor 550 gas chromatographic instrument. Separation was achieved with a FFAP packed column with a FID detector at 65°C.

Product analysis in the presence of $[Co(NH_3)_5Br](ClO_4)_2$

The products formed in the reaction between α-phenylethyl(aquo)-cobaloxime and $Co(NH_3)_5Br^{2+}$ were analyzed by ion chromatography and the cobalt thiocyanate spectrophotometric determination. Under deaerated conditions, α-phenylethyl(aquo)cobaloxime was reacted in 40% v/v methanol/water solution with excess acidic $Co(NH_3)_5Br^{2+}$ in a 50 mL volumetric flask. After completion of the reaction, 5.0 mL was analyzed for Co_{aq}^{2+} by the cobalt thiocyanate spectrophotometric method, with due correction for the absorption at 623 nm (14 cm^{-1} M^{-1}) by $Co(NH_3)_5Br^{2+}$. The remainder of the reaction mixture was placed on a column of SP Sephadex C-25 cation exchange resin in the H^+ form. The cationic species, Co_{aq}^{2+}, $(Co(dmgH)_2(H_2O)_2)^+$, and excess $Co(NH_3)_5Br^{2+}$,

were held in the resin while the uncharged $BrCo(dmgH)_2(H_2O)$ species was washed through the resin with water and 0.01 M $HClO_4$.

Bromo(aquo)cobaloxime was identified by its ultraviolet spectrum: 250 nm ($\sim 2 \times 10^4$ cm^{-1} M^{-1}) and 228 nm ($\sim 2 \times 10^4$ cm^{-1} M^{-1}) (24). The yellow $BrCo(dmgH)_2(H_2O)$ which eluted from the Sephadex column was converted to Co_{aq}^{2+} by digestion with 70% $HClO_4$ and analyzed by the cobalt thiocyanate method.

Rate determinations

The kinetics for the reaction of α-phenylethyl(aquo)cobaloxime with acid and various oxidizing agents were determined in solutions of 1.0 M ionic strength maintained with $HClO_4$ - $LiClO_4$. The reactions were followed by monitoring the decrease in absorbance of the organocobaloxime at 368 nm for each kinetic run. Experiments were conducted with the rigorous exclusion of air in 5.00 cm quartz cells. Temperature control was achieved by immersing the reaction cell in a small water bath positioned in the light beam of the Cary Model 219 spectrophotometer; this bath has quartz windows, and the water it contained was held at the desired temperature by circulation of water through an external jacket. Reactions were initiated by injecting a deaerated amount of α-phenylethyl(aquo)cobaloxime. The pseudo-first-order rate constant in each run was computed from the absorbance readings (D) as the negative of the slope of a plot of ln $(D_t - D_\infty)$ *vs.* time.

For the decomposition of α-phenylethyl(aquo)cobaloxime in the presence of tris(ethylenediamine)cobalt(III) perchlorate in neutral solution, the decrease in absorbance with time was monitored at 400 nm.

Tris(ethylenediamine)cobalt(III) perchlorate absorbs in the UV-visible spectrum at 465 nm (87 cm^{-1} M^{-1}) and 338 nm (78 cm^{-1} M^{-1}). Reactions were initiated by injecting a deaerated amount of α-phenylethyl(aquo)-cobaloxime into a cell containing $Co(en)_3^{3+}$, and upon completion, a second injection of the organocobaloxime was made. The first injection produces a constant amount of $Co^{II}(dmgH)_2(OH_2)$ in the system, and with each successive addition of α-phenylethyl(aquo)cobaloxime, the concentration of $Co^{II}(dmgH)_2(OH_2)$ increases accordingly.

Flash photolysis

Flash photolysis studies for the reaction of $Co(dmgH)_2(H_2O)$ with H^+ were carried out in 40% v/v methanol/water, and the ionic strength was maintained at 0.10 M with $HClO_4$ - $LiClO_4$. Appropriate volumes of methanol, water, $LiClO_4$, and $HClO_4$ were syringed into a cylindrical 10 cm quartz spectrophotometer cell and deaerated. The reaction was initiated by injecting a deaerated solution of α-phenylethyl(aquo)-cobaloxime, isopropyl(aquo)cobaloxime, or ethyl(aquo)cobaloxime into the cell. One hundred joule flashes were applied from fast-extinguishing Xenon flash lamps in the Xenon Corporation model 710 system. The Xenon lamps were filtered with Pyrex tubes to remove ultraviolet radiation. A storage oscilloscope was used to record the transmittance change accompanying the decay of the transient, which was monitored at the 460 nm (3.4×10^3 cm^{-1} M^{-1}) maximum for $Co(dmgH)_2(H_2O)$.

RESULTS AND DISCUSSION

Decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in the Presence of H^+

Kinetics

The rates of decay of the complexes $C_6H_5CH(CH_3)Co(dmgH)_2L$, for the axial ligands L = water and pyridine, were measured as a function of $[H^+]$. Values of the pseudo-first-order rate constant, k_{obs}, were the same, within experimental error, for both organocobaloximes. Because the rate constant for pyridine dissociation is higher and because free pyridine is protonated in acidic solution, the aquo derivative is the species present in acidic solution in either case (25). To optimize the solubility in 40% v/v methanol/water solution, the aquo derivative was used for most kinetic experiments.

The decomposition of α-phenylethyl(aquo)cobaloxime followed a pseudo-first-order rate law for all acid concentrations measured, $[H^+] = 1.38 \times 10^{-3}$ - 1.0 M (Equation 16).

$$-d[RCo(dmgH)_2(OH_2)] / dt = k_{obs}[RCo(dmgH)_2(OH_2)] \qquad (16)$$

A typical pseudo-first-order plot of ln $(D_t - D_\infty)$ vs. time is shown in Figure I-4 and in Table I-1 are listed k_{obs} values as a function of $[H^+]$. The values of k_{obs} obtained from the slopes of the pseudo-first-order plots are plotted vs. $[H^+]$ in Figure I-5. From the curvature of this plot, it is apparent that there is a complex dependence on $[H^+]$ for decomposition of α-phenylethyl(aquo)cobaloxime.

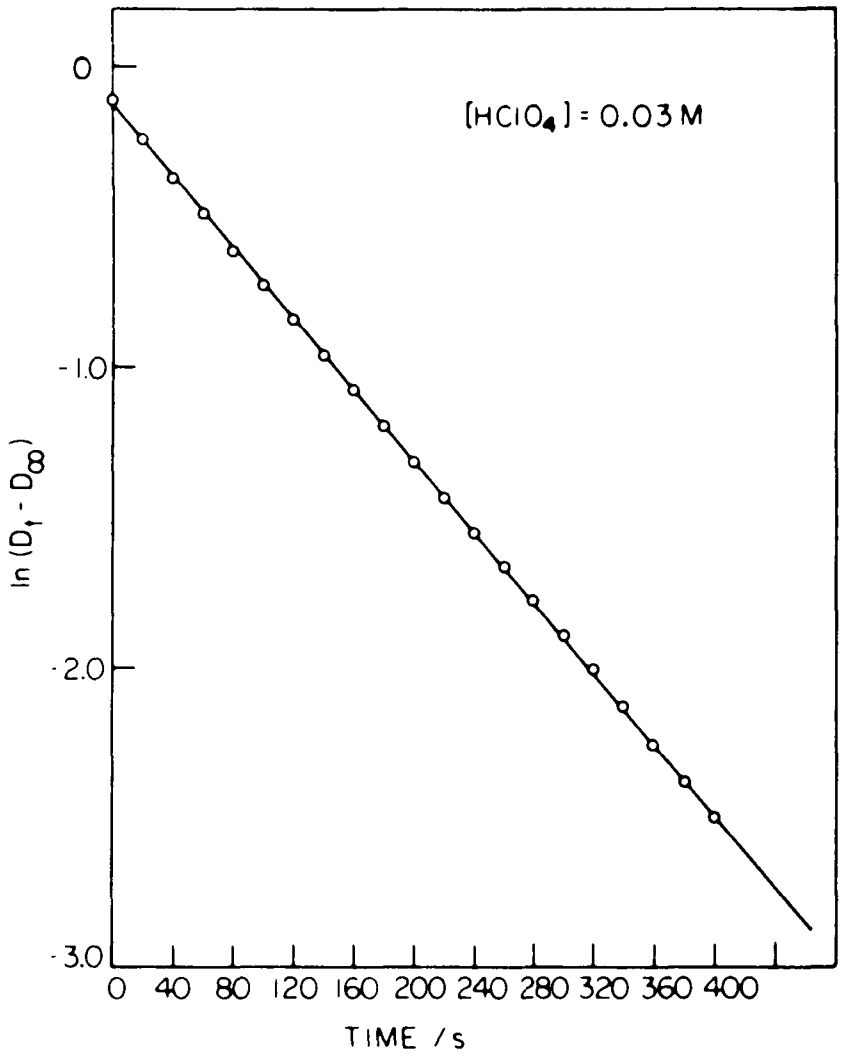


Figure I-4. Plot of ln $(D_t - D_\infty)$ vs. time for the decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in 0.03 M H^+ solution

Table I-1. The kinetics of decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in acidic solution[a]

$[H^+]$/M	$10^3\ k_{obs}/s^{-1}$
0.00138	3.65
0.00550	4.13
0.00830	4.22
0.0200	5.01
0.0300	5.90
0.0500	6.89
0.0600	7.53
0.0700	8.06
0.0900	8.37
0.100	8.56
0.120	9.01
0.130	9.25
0.150	9.81
0.170	10.2
0.180	10.1
0.200	10.5
0.240	10.8
0.300	11.3
0.400	11.7
0.500	12.4
0.600	12.8
0.700	13.0
0.800	13.4
0.900	13.9
1.00	14.3

[a] $T = 25.0°C$; $\mu = 1.0$ M ($LiClO_4$); $[C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)] \sim 1 \times 10^{-5}$ M; solvent: 40% v/v methanol/water.

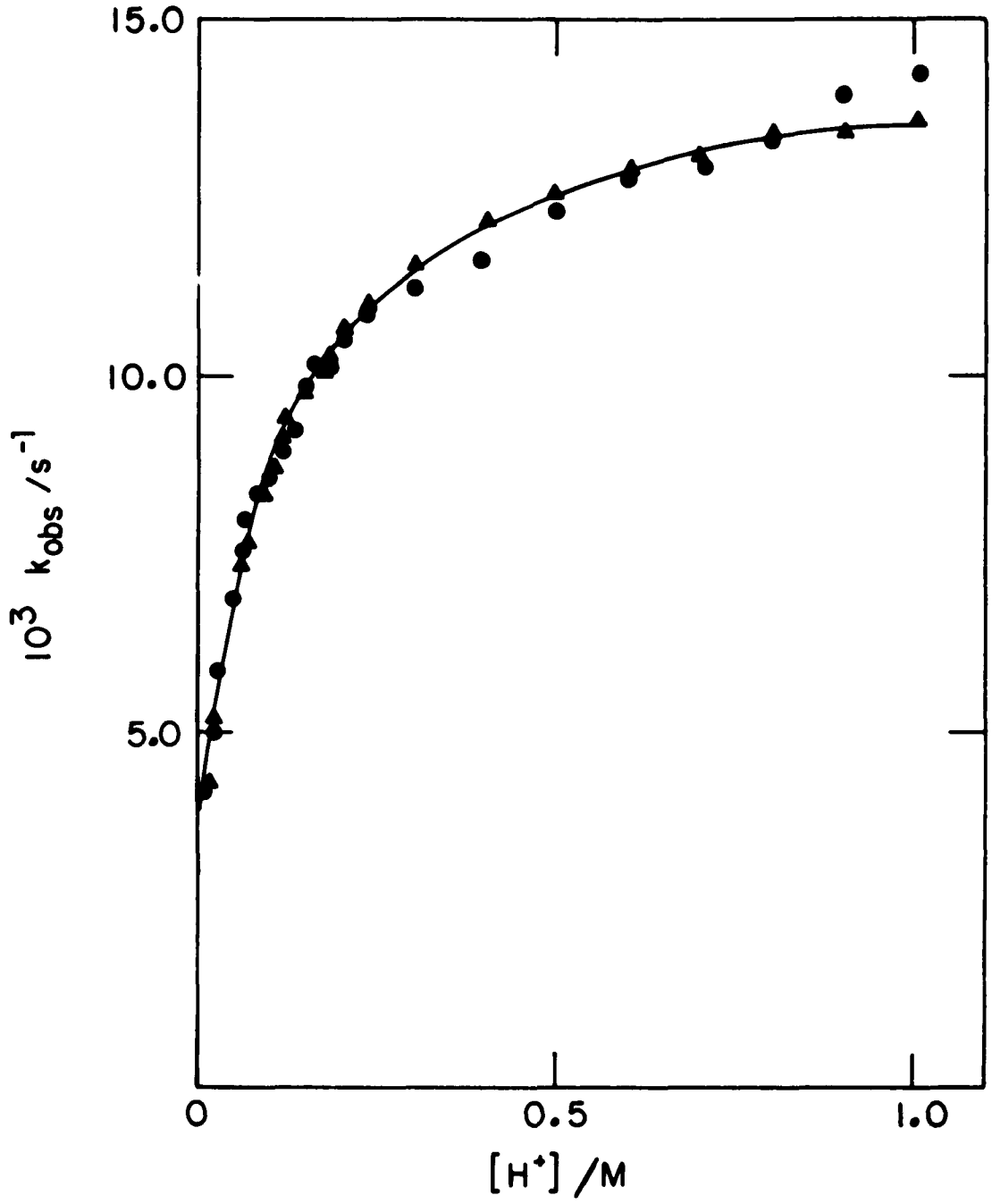


Figure I-5. Plot of k_{obs} vs. $[H^+]$ for the decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$; actual (circles), calculated according to Equation 27 (triangles)

Alkylcobaloximes are known to undergo a rapid and reversible equilibrium reaction with H^+ (26-31). In the equilibrium, one of the two pairs of hydrogen-bonded O-H --- O units is converted to two separate OH units. The equilibrium is symbolized as:

$$RCo(dmgH)_2(OH_2) + H^+ \underset{}{\overset{K_H}{\rightleftharpoons}} RCo(dmg_2H_3)(OH_2)^+ \quad (17)$$

Values of K_H typically lie in the range 1-4 M^{-1} for various alkyl and aryl R groups (26,28,30). A plausible mechanism which would account for the curvature of the plot of k_{obs} vs. $[H^+]$ is given in Equations 18-22.

$$C_6H_5CH(CH_3)Co(dmgH)_2(OH_2) + H^+ \underset{}{\overset{K_H}{\rightleftharpoons}} C_6H_5CH(CH_3)Co(dmg_2H_3)(OH_2)^+ \quad (18)$$

$$C_6H_5CH(CH_3)Co(dmg_2H_3)(OH_2)^+ \xrightarrow{k_a} C_6H_5\dot{C}HCH_3 + Co(dmg_2H_3)(OH_2)^+ \quad (19)$$

$$C_6H_5CH(CH_3)Co(dmgH)_2(OH_2) \xrightarrow{k_b} C_6H_5\dot{C}HCH_3 + Co(dmgH)_2(OH_2) \quad (20)$$

$$Co(dmg_2H_3)(OH_2)^+ + H^+ \xrightarrow{fast} Co_{aq}^{2+} + 2H_2dmg \quad (21)$$

$$Co(dmgH)_2(OH_2)^+ + 2H^+ \xrightarrow{fast} Co_{aq}^{2+} + 2H_2dmg \quad (22)$$

In the above series of reactions, homolysis of the cobalt-alkyl bond is shown as the rate-limiting step for the decomposition of the organocobaloxime. Another mechanism which is just as reasonable might invoke β-elimination after the pre-equilibrium step (Equations 23-24), the resulting hydridocobaloxime then very rapidly yielding products, perhaps by the reactions shown (Equations 25-26), or possibly by other rapid reactions.

$$C_6H_5CH(CH_3)Co(dmg_2H_3)(OH_2)^+ \xrightarrow{k_a} C_6H_5CH{=}CH_2 + HCo(dmg_2H_3)(OH_2)^+ \quad (23)$$

$$C_6H_5CH(CH_3)Co(dmgH)_2(OH_2) \xrightarrow{k_b} C_6H_5CH{=}CH_2 + HCo(dmgH)_2(OH_2) \quad (24)$$

$$HCo(dmg_2H_3)(OH_2)^+ + H^+ \xrightarrow{k_1} Co_{aq}^{2+} + 1/2\ H_2 + 2H_2dmg \quad (25)$$

$$HCo(dmgH)_2(OH_2) + 2H^+ \xrightarrow{fast} Co_{aq}^{2+} + 1/2\ H_2 + 2H_2dmg \quad (26)$$

The proposed homolytic and β-elimination mechanism lead to Equation 27, provided the subsequent steps leading to Co_{aq}^{2+} occur rapidly.

$$k_{obs} = \frac{k_b + k_aK_H[H^+]}{1 + K_H[H^+]} \quad (27)$$

A good correlation of the kinetic data to a plot of $k_{obs}\ (1 + K_H[H^+])$ vs. $[H^+]$ is shown in Figure I-6. A nonlinear least squares computer analysis of the kinetic data resulted in the following values:

$$k_b = (3.55 \pm 0.07) \times 10^{-3}\ s^{-1}$$

$$k_aK_H = (1.23 \pm 0.05) \times 10^{-1}\ s^{-1}\ M^{-1}$$

$$k_a = (1.48 \pm 0.14) \times 10^{-2}\ s^{-1}$$

$$K_H = 8.33 \pm 0.44\ M^{-1}$$

The value of K_H is slightly larger than those found for alkyl or other aralkyl cobaloximes, 1-4 M^{-1}, but not by a large amount. The values reflect the small amount of basicity inductively transmitted from the α-phenylethyl carbanion to the oxime oxygens. Most of the

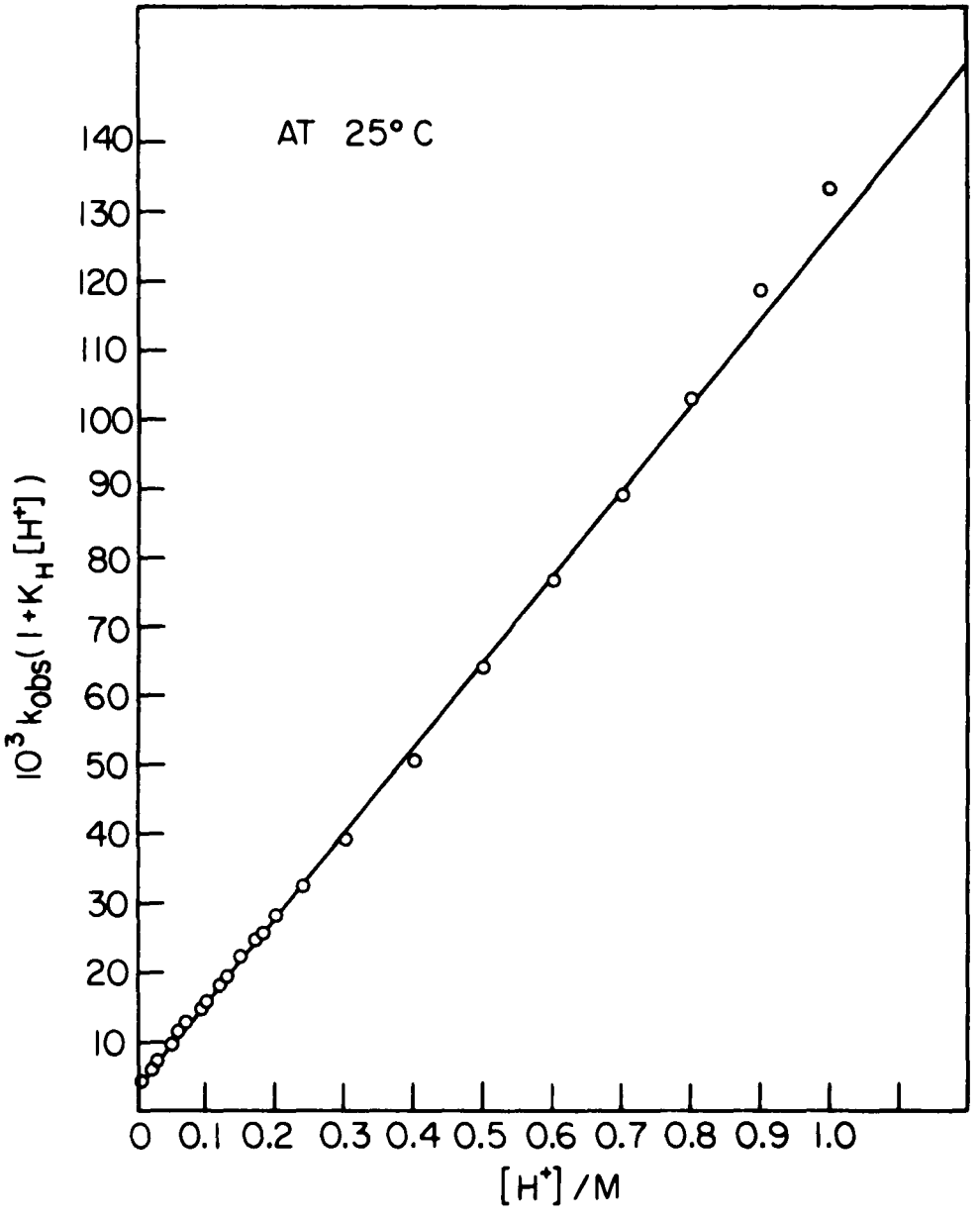


Figure I-6. Plot of k_{obs} $(1 + K_H[H^+])$ <u>vs.</u> $[H^+]$

basicity is expended on the formation of the covalent bond between Co(III) and R^-.

Inorganic products

The assumption that Co_{aq}^{2+} is the final product of a homolytic or β-elimination mechanism was proved by direct measurement following the decomposition reactions. The complete conversion of α-phenylethyl-(aquo)cobaloxime into Co_{aq}^{2+}, independently of $[H^+]$, is shown in Table I-2.

Table I-2. Formation of Co_{aq}^{2+} from thermal and photochemical decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$[a]

10^4 $[RCo(dmgH)_2]$/M	$[H^+]$/M	10^4 $[Co_{aq}^{2+}]$/M
1.01[b]	0.01	1.03
1.06[b]	0.10	1.03
41.1[c]	0.13	40.3
1.08[b]	0.60	1.08

[a]At 25.0°C in aqueous methanol; μ = 1.0 M.

[b]Thermal decomposition.

[c]Photochemical decomposition.

Organic products

Quantitative analysis of the organic products resulting from decomposition of α-phenylethyl(aquo)cobaloxime in acidic 40% v/v methanol/water solution could conclusively distinguish between β-elimination and homolysis as the rate-limiting step of the decomposition reaction. Complete conversion of the organocobaloxime to styrene would be consistent with the β-elimination process proposed by earlier workers in neutral solution (16). A homolytic rate determining step resulting in α-phenylethyl radicals could lead to a mixture of dimeric and disproportionation products.

The product distribution from α-phenylethyl radicals has been studied. When Green generated α-phenylethyl radicals from SS-(-)-azobis-α-phenylethane and from meso-azobis-α-phenylethane in benzene, the dimeric products observed from both compounds were meso- and d,ℓ-2,3-diphenylbutane formed in roughly equal amounts with a total yield of 88% (32). The remaining 12%, although not identified, was ascribed to disproportionation to afford styrene and ethylbenzene. Similar results of 1:1 meso- and d,ℓ-2,3-diphenylbutane from α-phenylethyl radicals had been reported earlier (33). The reduction of α-phenylethyl chloride and α-phenylethyl bromide by Cr^{2+} leads to dimerization of the alkyl group with 85-90% meso-2,3-diphenylbutane and 10-15% d,ℓ-2,3-diphenylbutane stereochemistry (34). The fact that reductive coupling in this system is the result of a direct attack of Cr^{2+} on the organic halide to produce a free radical which subsequently dimerizes may account for the different product distribution. In the Cr^{2+} system, it is unclear

whether the radical produced is entirely free or loosely affiliated with the metal ion, and whether the ions present influence the dimerization process. The ability of metal ions to mediate the dimerization of free radicals has been demonstrated (35).

Dimeric compounds, as well as styrene, were found from the decomposition of α-pnenylethyl(aquo)cobaloxime in acidic solution. Disproportionation was ruled out as a feasible decomposition process since no ethylbenzene was observed in the product mixture. The gas-liquid chromatographic trace of the four dimeric compounds (A-D) and their internal standard, bibenzyl, are shown in Figure I-7. The exact mass of each of the compounds was the same for the molecular formula, $C_{16}H_{18}$:

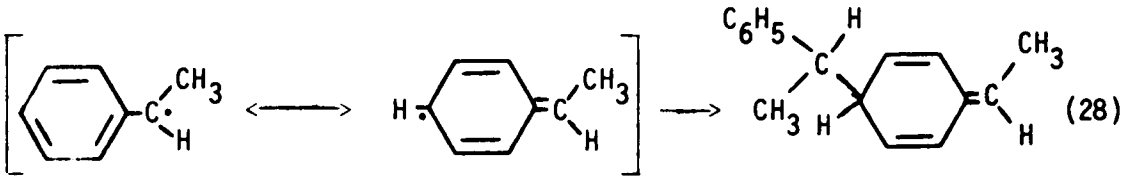
measured exact mass = 210.14095

calculated exact mass = 210.14085

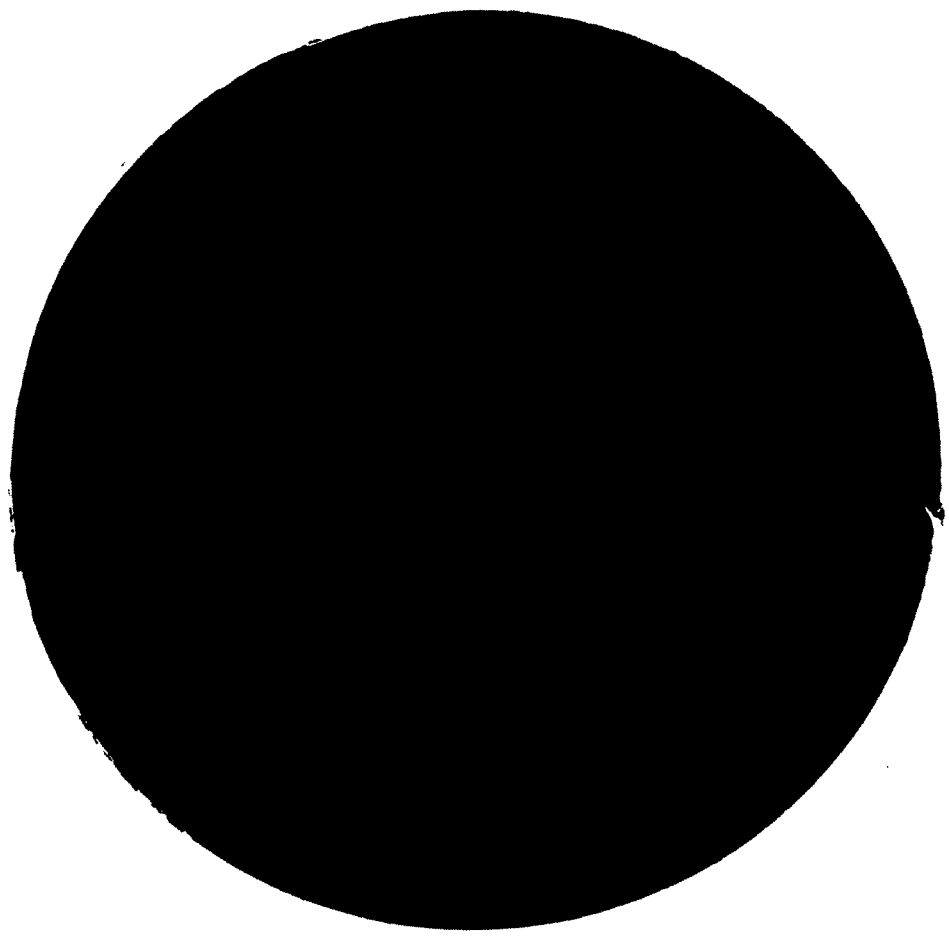
error = ± 0.5 ppm

Based on the mass spectral fragmentation patterns (Figures I-8 - I-11), the structures assigned to the four dimeric compounds are shown in Figure I-12. Compounds A and B are meso- and d,ℓ-2,3-diphenylbutane, respectively. Compound C is di-α-phenylethyl quinoid (1-ethylidene-4(α-phenylethyl)cyclohexa-2,5-diene) and D is 1,3-diphenylbutane.

The unusual structure assigned to dimer C is believed to arise from α-to-para coupling of α-phenylethyl radicals (Equation 28).



(28)



. Gas-liquid chrom[illegible] bibenzyl, A, B, C, and [illegible] packed col[illegible] at 150°C,

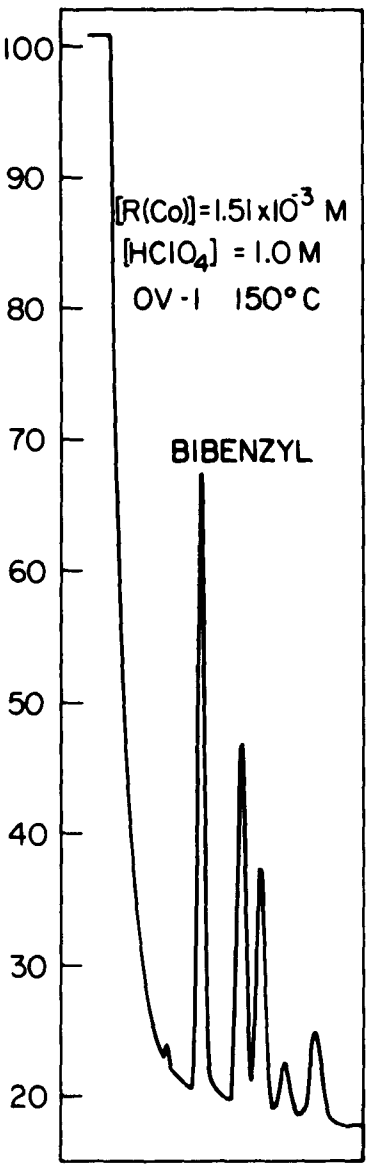


Figure I-7. Gas-liquid chromatographic trace of internal standard, bibenzyl, A, B, C, and D in order of appearance on OV-1 packed column at 150°C; sample injection 2 µl

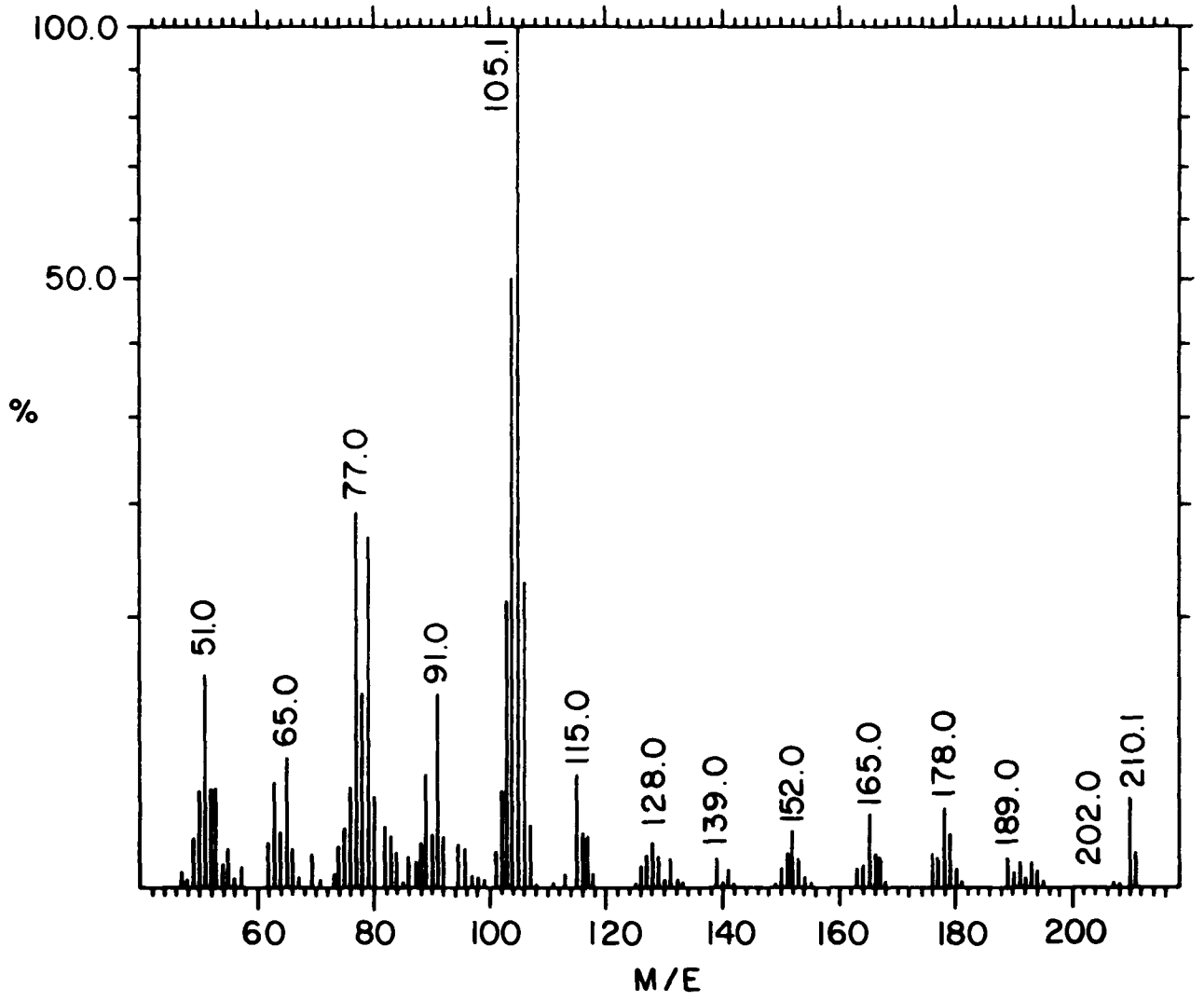


Figure I-8. Mass spectrum of meso-2,3-diphenylbutane

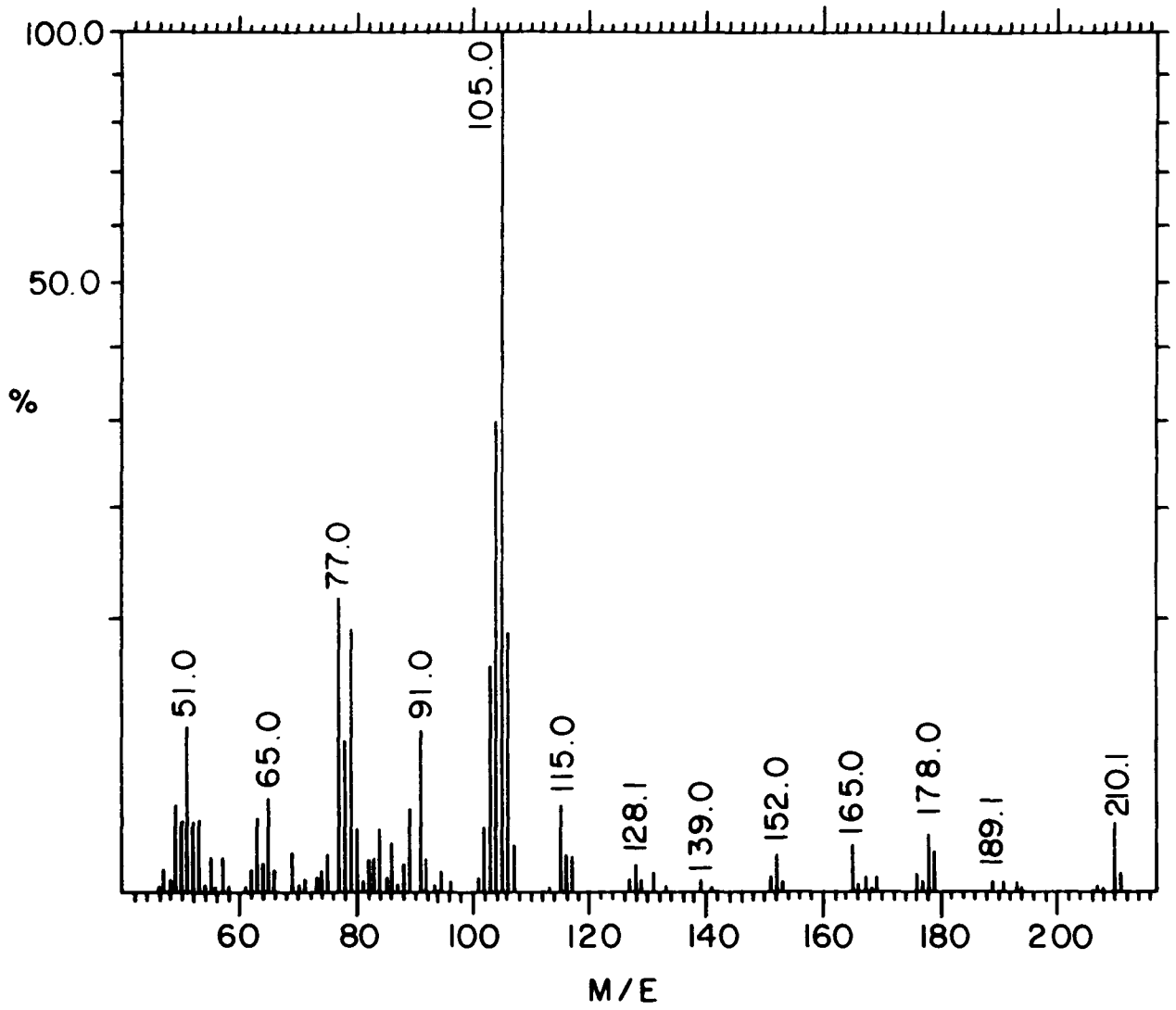


Figure I-9. Mass spectrum of d,ℓ-2,3-diphenylbutane

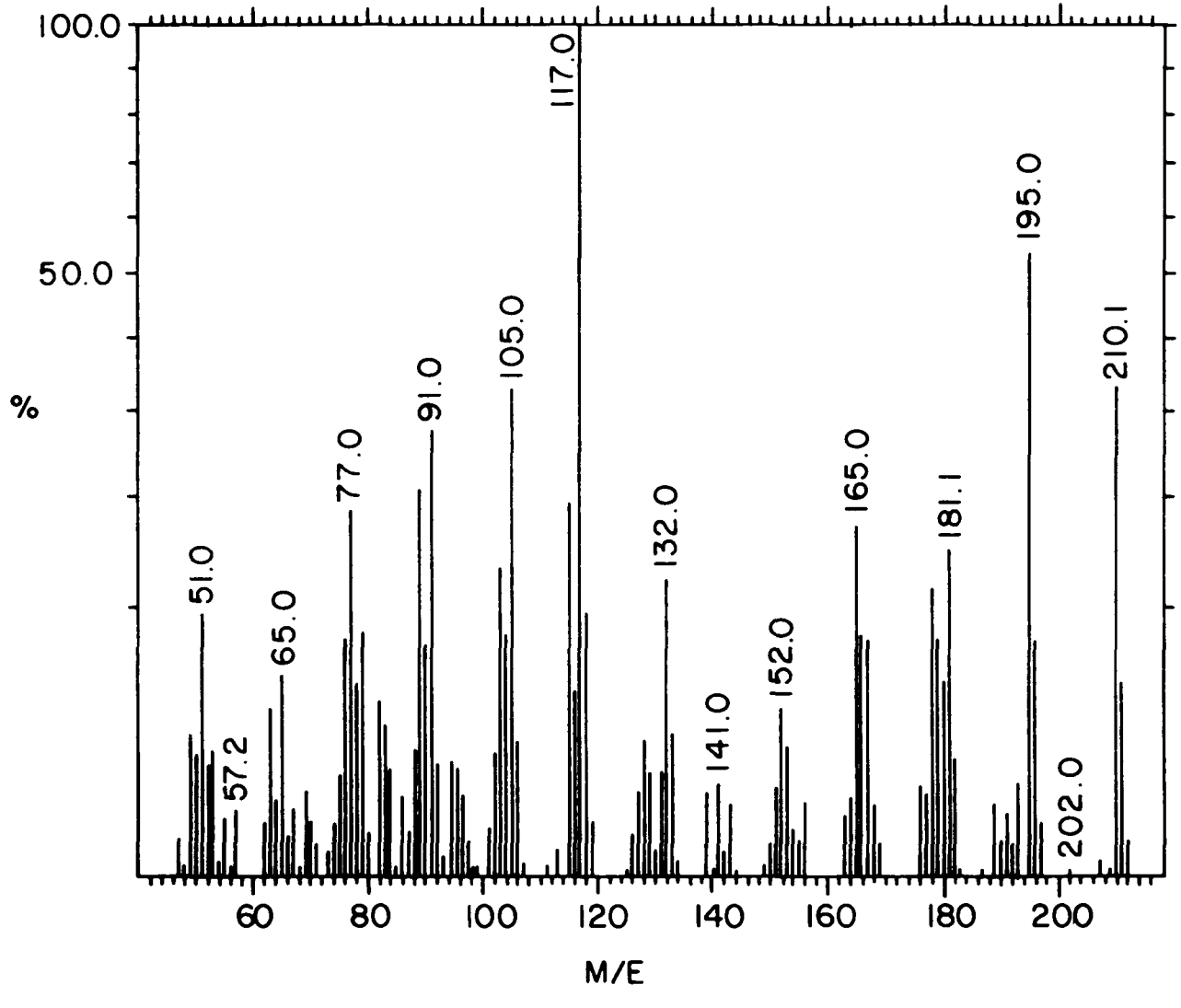


Figure I-10. Mass spectrum of di-α-phenylethyl quinoid

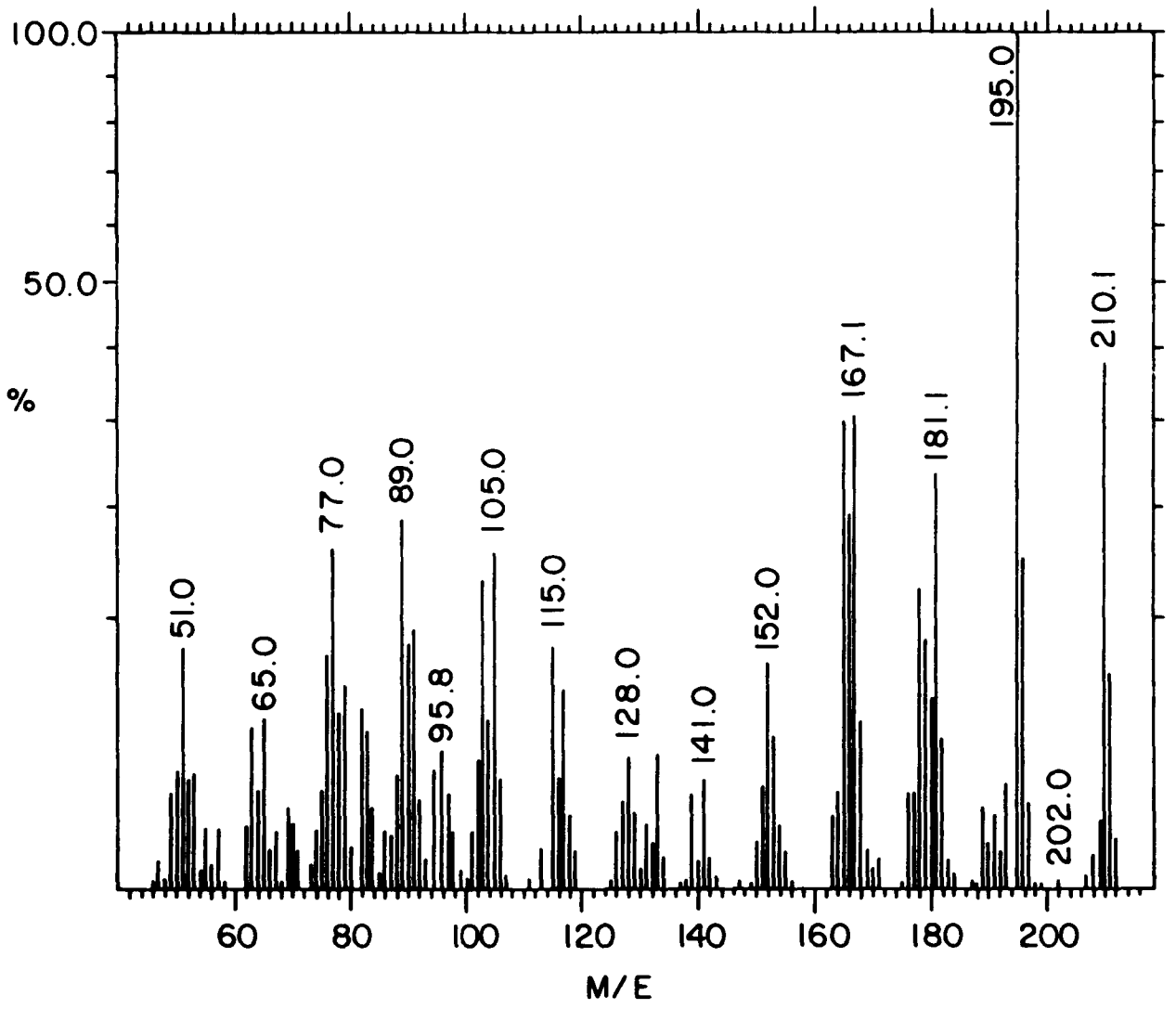
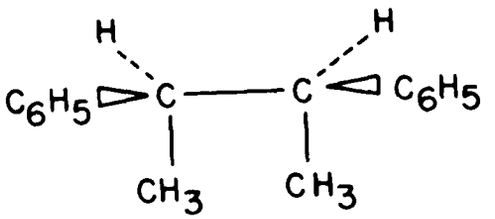
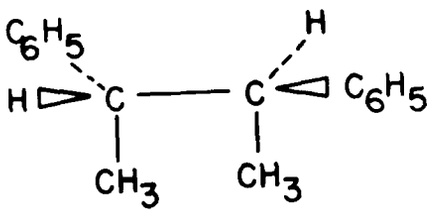
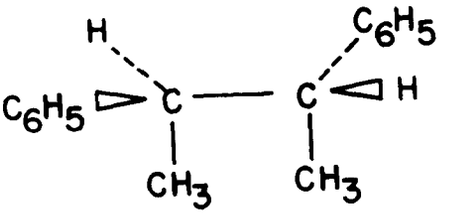


Figure I-11. Mass spectrum of 1,3-diphenylbutane

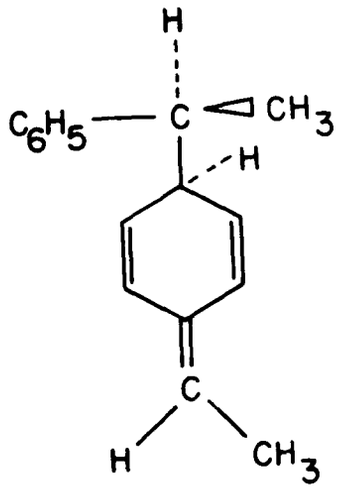


A

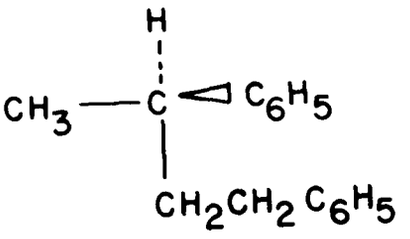




B



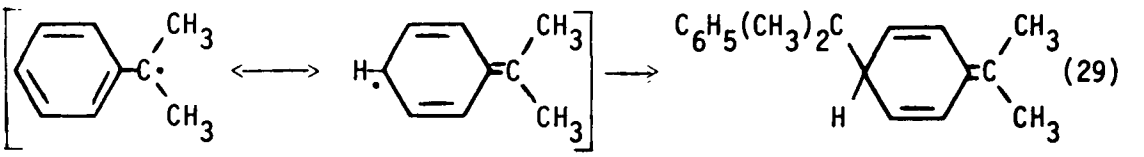
C



D

Figure I-12. Molecular structures assigned to four dimeric compounds: A = meso-2,3-diphenylbutane; B = d,ℓ-2,3-diphenylbutane; C = di-α-phenylethyl quinoid; D = 1,3-diphenylbutane

A precedent for this type of quinoid compound was found in the dimeric products of cumyl radicals (36). A portion of the coupling products, estimated as about 2%, was dicumyl quinoid, formed by dimerization of cumyl radicals at the <u>para</u> position (Equation 29).



(29)

There is a pronounced difference in the stabilities of dicumyl and di-α-phenylethyl quinoid; dicumyl quinoid is quite unstable, but di-α-phenylethyl quinoid lasts for at least two days without decomposing. The difference in stability between the two coupling products is undoubtedly a matter of decreased steric hindrance at the α-carbon site for di-α-phenylethyl quinoid.

Although quinoid products from <u>para</u> attack of radicals on triphenylmethyl radical have been in the literature for a long time (37), there is little known concerning such attack on less hindered radicals.

Compound D, 1,3-diphenylbutane, can be explained if there is some hydridocobaloxime present in the reaction mixture. Beta attack by hydridocobaloxime on styrene is the favorable mode of addition, but a certain percentage of the reaction probably proceeds by alpha attack to form β-phenylethyl(aquo)cobaloxime. A displacement reaction between α-phenylethyl radical, produced during homolysis, and β-phenylethyl-(aquo)cobaloxime would lead to dimer D as shown in Equations 30 and 31.

$$C_6H_5CH{=}CH_2 + HCo(dmgH)_2(OH_2) \longrightarrow C_6H_5CH_2CH_2Co(dmgH)_2(OH_2) \qquad (30)$$

$$C_6H_5CH_2CH_2Co(dmgH)_2(OH_2) + C_6H_5\dot{C}HCH_3 \longrightarrow C_6H_5CH_2CH_2CH(CH_3)C_6H_5 + Co(dmgH)_2(OH_2) \quad (31)$$

In Table I-3 are given the concentrations of coupling products and styrene obtained during the gas-liquid chromatographic analysis. The greater than 100% yield in organic products results from error inherent in the experimental technique.

The dimeric compounds, A, B and C, arise from α-phenylethyl radical coupling reactions; styrene and compound D result from β-elimination of α-phenylethyl(aquo)cobaloxime. Styrene is a direct product of β-elimination and compound D comes about indirectly through reaction of hydridocobaloxime.

In good agreement with the 1:1 ratio of meso- to d,ℓ-2,3-diphenylbutane observed by previous workers (32,33) for the coupling products of α-phenylethyl radicals in neutral solution, compounds A and B were found in approximately equal molar amounts. A new compound, C, di-α-phenylethyl quinoid, which was not observed in earlier work, was produced in about 10% yield.

In Table I-5 is the product distribution resulting from β-elimination. It is clear from Tables I-4 and I-5 that the organic product distribution is independent of acid concentration. The percent decomposition of the organocobaloxime by homolytic cobalt-carbon bond cleavage and the percent of β-elimination are shown in Table I-6.

On the average, 72% of the original α-phenylethyl(aquo)cobaloxime undergoes homolysis and 28% decomposes by β-elimination. This result is somewhat of a compromise between the mechanistic interpretations proposed earlier (16,17) for the decomposition of α-phenylethyl(aquo)cobaloxime.

Table I-3. Quantitative determination of organic products from decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$

$10^3[RCo(dmgH)_2]/M$	$[H^+]/M$	$10^5[A]^a/M$	$10^5[B]^a/M$	$10^5[C]^a/M$	$10^5[D]^a/M$	$10^5[C_6H_5CH{=}CH_2]^b/M$	Total %
0.49	5×10^{-3}	8.58	7.84	1.94	3.92	7.07	105
1.50	0.10	---	---	---	---	17.7	---
1.54	1.0	32.2	22.2	5.83	11.4	22.7	108

[a]GC analysis on OV-1 packed column at 150°C.

[b]GC analysis on FFAP packed column at 65°C.

Table I-4. Organic products from α-phenylethyl radical coupling

$10^3[RCo(dmgH)_2]/M$	$[H^+]/M$	%A	%B	%C	$10^5[A+B+C]_{total}/M$
0.49	5×10^{-3}	46.7	42.7	10.6	18.4 (71.1%)[a]
1.54	1.0	53.5	36.9	9.7	60.2 (72.6%)

[a]Percentages normalized to 100%.

Table I-5. Organic products from $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ β-elimination

$10^3[RCo(dmgH)_2]/M$	$[H^+]/M$	%D	$\%C_6H_5CH=CH_2$	$10^5[2D+C_6H_5CH=CH_2]/M$
0.49	5×10^{-3}	52.6	47.4	14.9 (28.9%)[a]
1.54	1.0	50.1	49.9	45.5 (27.4%)

[a]Percentages normalized to 100%.

Table I-6. Product distribution percentages for radical coupling and β-elimination decomposition processes

$10^4[2A+2B+2C]/M$	$10^4[2D+C_6H_5CH=CH_2]/M$	% Radical Coupling	% β-elimination
1.84	1.10	71.1	28.9
6.02	3.41	72.6	27.4

Scheme I-1 illustrates the concurrent pathways for decomposition of the protonated and unprotonated organocobaloxime where k_a and k_b are the first-order rate constants for the decay of each form of α-phenylethyl-(aquo)cobaloxime.

Determination of activation parameters

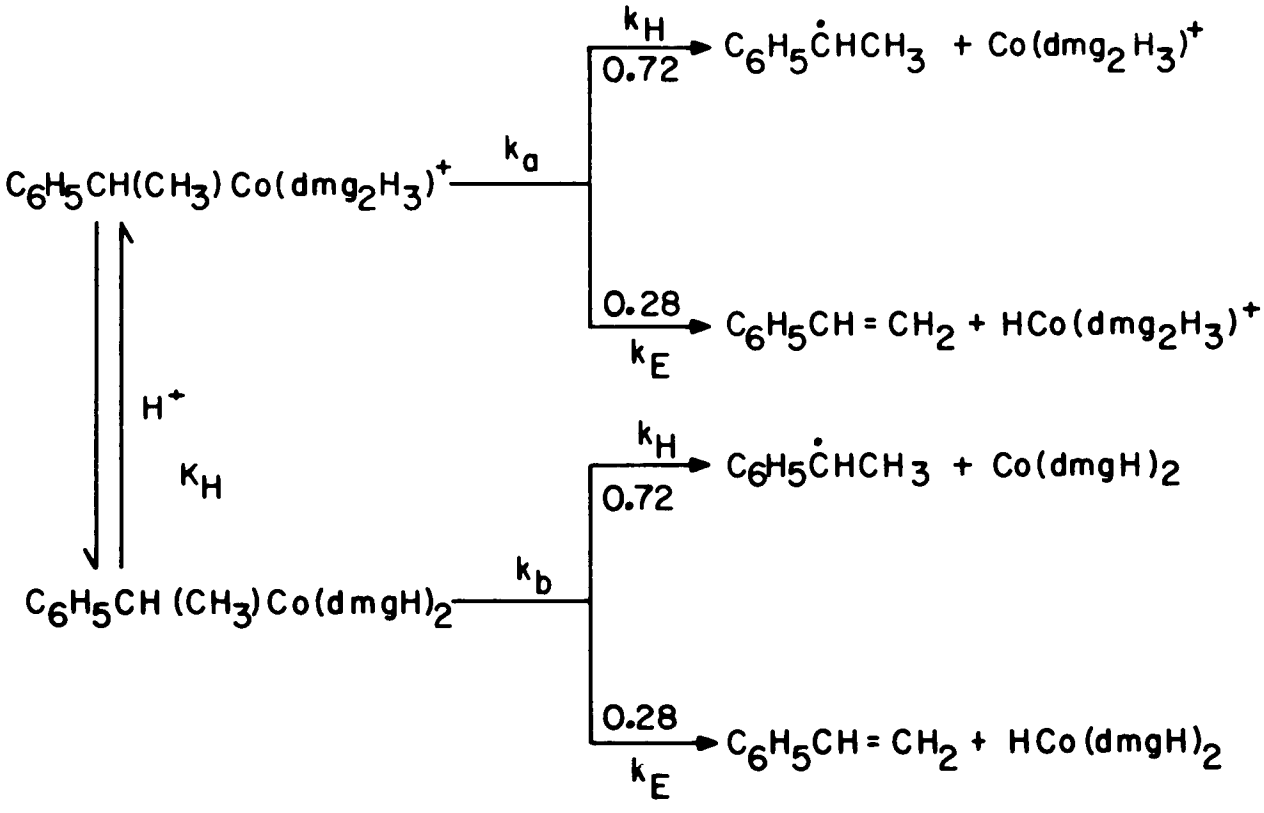
The decomposition of α-phenylethyl(aquo)cobaloxime in acidic solution was studied at several temperatures to obtain the activation parameters for the process. At each temperature, the decay of the organocobaloxime was studied under pseudo-first-order conditions, and $[H^+]$ was varied 5×10^{-3} - 1.0 M. Using a nonlinear least squares computer analysis of k_{obs} values, k_a and k_b are listed in Table I-7 as a function of temperature. The value of K_H remains fairly constant with change in temperature, 7.4 ± 1.1 M^{-1}.

Table I-7. Rate constants for decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ as a function of temperature[a]

T/°C	$10^3k_b/s^{-1}$	$10^2k_a/s^{-1}$	$10^1k_aK_H/s^{-1}M^{-1}$	K_H/M^{-1}
15.0	0.75 ± 0.04	0.33 ± 0.05	0.18 ± 0.02	5.4
25.0	3.55 ± 0.07	1.48 ± 0.14	1.23 0.05	8.31
35.0	14.67 ± 0.90	5.86 ± 0.82	4.32 0.38	7.37
40.0	31.06 ± 1.44	10.53 ± 1.44	9.06 0.76	8.60

[a] μ = 1.0 M ($LiClO_4$).

Scheme I-1


$C_6H_5CH(CH_3)Co(dmg_2H_3)^+$
k_a
k_H
0.72
$C_6H_5\dot{C}HCH_3 + Co(dmg_2H_3)^+$
0.28
k_E
$C_6H_5CH=CH_2 + HCo(dmg_2H_3)^+$
H^+
K_H
$C_6H_5CH(CH_3)Co(dmgH)_2$
k_b
k_H
0.72
$C_6H_5\dot{C}HCH_3 + Co(dmgH)_2$
0.28
k_E
$C_6H_5CH=CH_2 + HCo(dmgH)_2$

The activation parameters were computed by combining Equations 27 and 32 so that values of k_a and k_b were defined in terms of the Eyring equation.

$$k_x = \frac{RT}{Nh} \exp\left(\frac{-\Delta H_x^{\ddagger}}{RT} + \frac{\Delta S_x^{\ddagger}}{R}\right) \tag{32}$$

The value of k_H obtained from this analysis is 8.13 ± 0.38 M^{-1}. The results are tabulated in Table I-8.

Table I-8. Activation parameters for decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in acidic solution

k_x/s^{-1}	$\Delta H^{\ddagger}/k_{cal}$ mol^{-1} kcal	$\Delta S^{\ddagger}$/cal mol^{-1} deg^{-1}
k_b	28.55 ± 1.14	25.65 ± 3.63
k_a	23.23 ± 0.22	11.08 ± 0.70

The value of $\Delta H^{\ddagger}$ is in reasonably good agreement with the enthalpy Halpern et al. measured in toluene for the decomposition of α-phenylethyl(py)cobaloxime ($\Delta H^{\ddagger}$ = 21.2 ± 0.5 kcal mol^{-1}), but in poor agreement with the entropy ($\Delta S^{\ddagger}$ = 1.4 ± 1.5 cal mol^{-1} deg^{-1}) (17). A large positive value of $\Delta S^{\ddagger}$, found in this work, is consistent with a mechanism which invokes substantial decomposition by a homolytic pathway. The more polar solvent, 40% v/v methanol/water, may have an unexpected effect on the magnitude of $\Delta S^{\ddagger}$ in these decomposition studies. The effect might be because homolysis is much more important in aqueous methanol than in toluene, or because the hydrocarbon radical disrupts

the structure of the polar solvent much more, giving an increased value of $\Delta S^{\ddagger}$.

Kinetics of Reaction of $Co(dmgH)_2(OH_2)$ with H^+

The reaction between $Co(dmgH)_2(OH_2)$ and acid is very rapid; in 0.001 M H^+, for example, it proceeds to completion at a rate too high for the stopped-flow method. Decomposition of $Co(dmgH)_2(OH_2)$ has been studied in acetate buffers of pH 4.8-6.1 (24). Kinetic data were needed at higher acid concentrations if competition experiments were to be carried out between H^+ and an oxidant for reaction with $Co(dmgH)_2(OH_2)$, produced by homolysis of α-phenylethyl(aquo)cobaloxime. Flash photolysis afforded a way to photochemically generate $Co(dmgH)_2(OH_2)$ and monitor its decay in acidic solution.

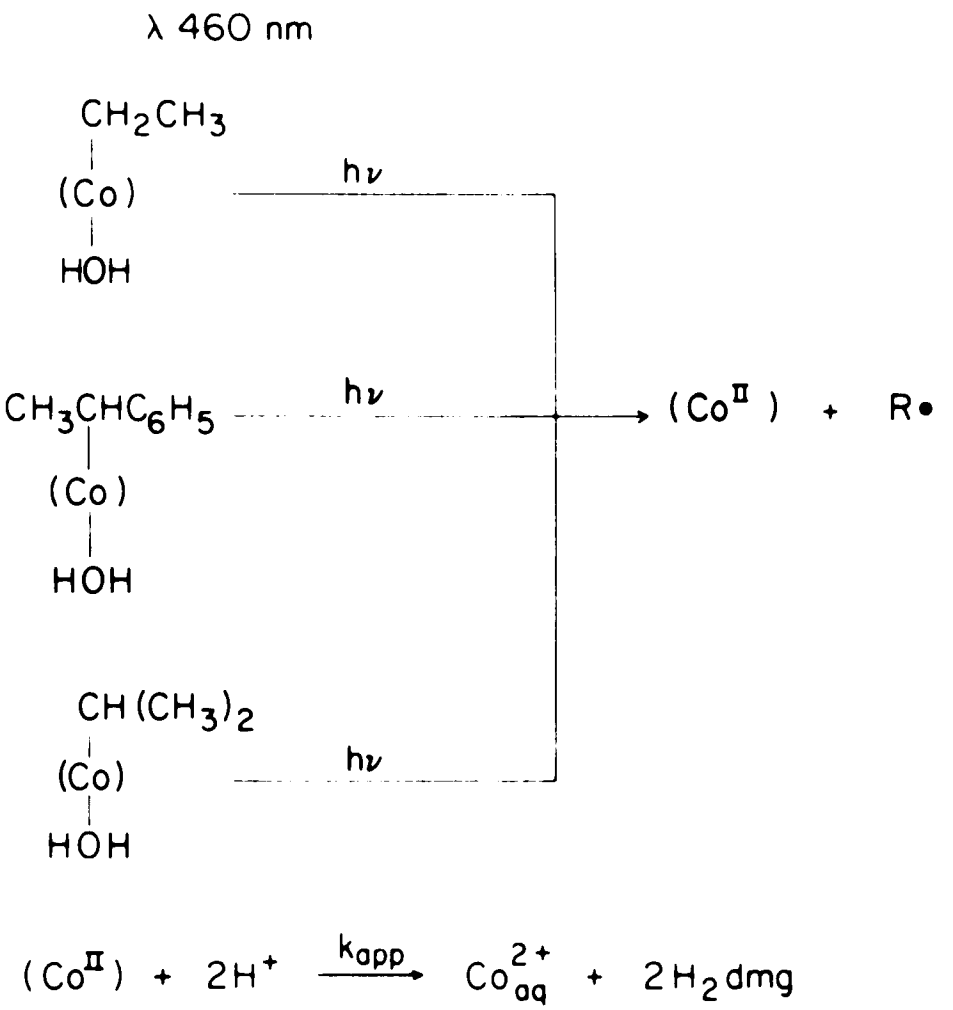
The design of the kinetic experiments was to independently flash three different organocobaloximes in acidic solution, and follow the decrease in absorbance of the presumed intermediate, $Co(dmgH)_2(OH_2)$, with time. The three organocobaloximes tested were α-phenylethyl(aquo)-cobaloxime, ethyl(aquo)cobaloxime, and isopropyl(aquo)cobaloxime. For each organocobaloxime, linear pseudo-first-order plots of $\ln (D_t - D_\infty)$ *vs.* time were obtained where $[H^+] = (0.36 - 5.35) \times 10^{-3}$ M. The typical organocobaloxime concentration was 5×10^{-5} M. The acid concentration range was limited because at higher concentrations, the rate of reaction exceeded the time scale of the flash photolysis experiments, $\leq 10^4$ s^{-1}.

The reaction studied is represented by Equation 33 and Scheme I-2.

$$Co(dmgH)_2(OH_2) + 2H^+ \xrightarrow[H_2O]{k_{app}} Co_{aq}^{2+} + 2H_2dmg \qquad (33)$$

The complex dependence of k_{app} on $[H^+]$ is shown in Figure I-13. Values of k_{app} are nearly identical at a particular acid concentration for each organocobaloxime which is indicative of a common intermediate, $Co(dmgH)_2(OH_2)$, being generated from each compound. The variation of k_{obs} with $[H^+]$ is not linear, and it is very likely of a complex form since pre-equilibrium protonation steps may occur, and since H_3O^+ and H_2O may react in parallel pathways. The intention of these experiments is to detect the $Co(dmgH)_2(OH_2)$ complex in competition experiments, so there is no need to describe the variation of k_{obs} with $[H^+]$ in an algebraic form; the value of k_{obs} at a particular $[H^+]$ is the important quantity. It might be noted, however, that the likely role of H^+ in this process is protonation of both oxygens on the dimethylglyoxime ligands, thereby destroying the O---H—O hydrogen bonding which lends great stability to these complexes. Independent evidence exists for the importance of each protonation in $Co^{III}(dmgH)_2(OH_2)_2$ complexes (26,38). The pseudo-first-order rate constant at a given acid concentration for this reaction is designated k_{app}^H. Competition studies were performed within the acid concentration range $(0.36 - 5.35) \times 10^{-3}$ M used in the evaluation of k_{app}^H.

Scheme I-2


λ 460 nm
CH2CH3
(Co)
HOH
hν
CH3CHC6H5
(Co)
HOH
hν
(Co^II) + R•
CH(CH3)2
(Co)
HOH
hν
(Co^II) + 2H+ kapp Co2+aq + 2H2dmg

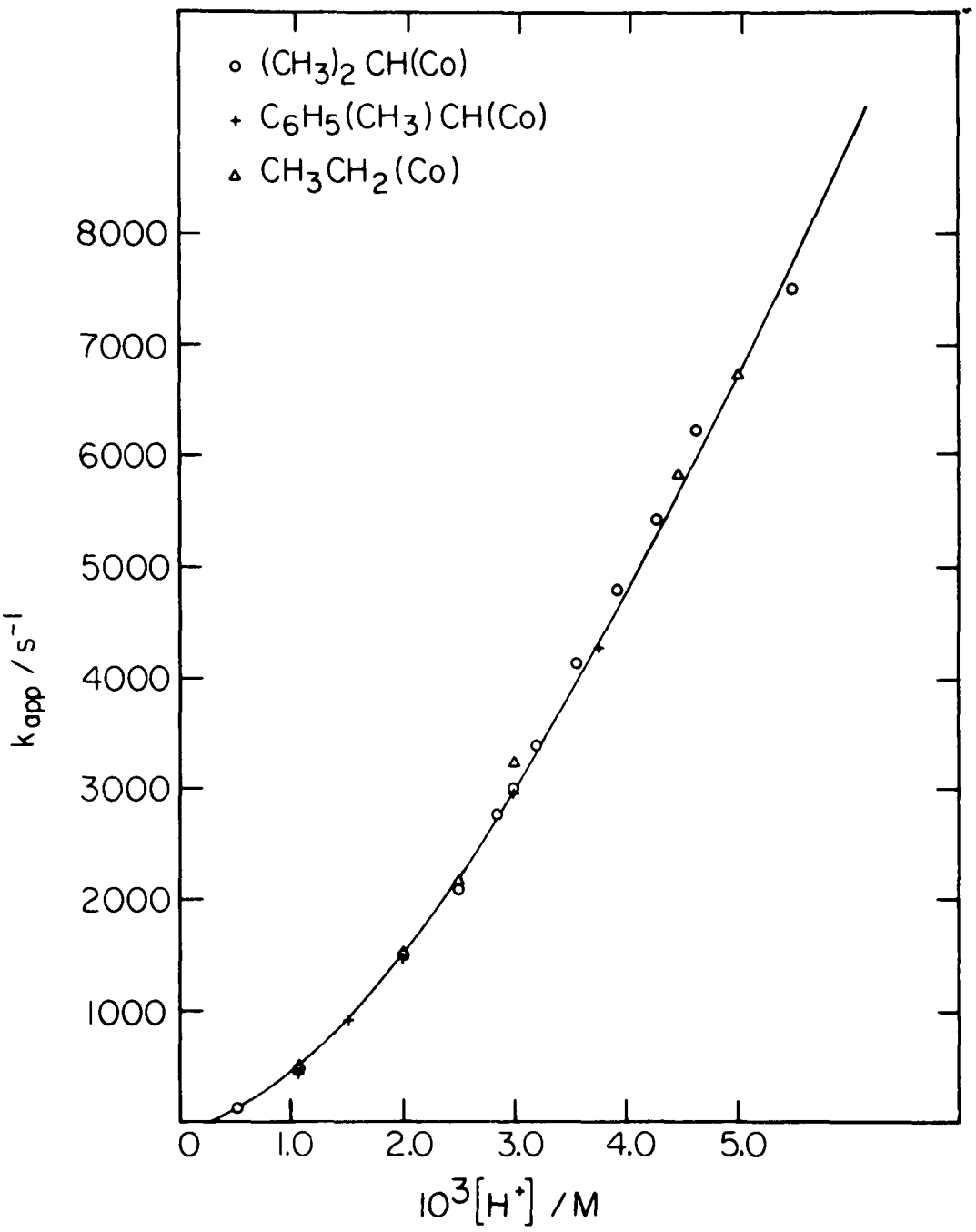


Figure I-13. Plot of k_{app} vs. $[H^+]$ for the reaction of $Co(dmgH)_2(OH_2)$ with H^+

Decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in the Presence of H_2O_2 and $Co(NH_3)_5Br^{2+}$

Kinetics

The reaction between $Co(dmgH)_2(OH_2)$ and H_2O_2 was previously studied, and the kinetic data were in accord with the rate law in Equation 34, where $k_{H_2O_2} = (1.92 \pm 0.20) \times 10^3\ M^{-1}\ s^{-1}$ and is independent of $[H^+]$ (39).

$$-d[Co(dmgH)_2(OH_2)]/dt = k_{H_2O_2}\,[Co(dmgH)_2(OH_2)][H_2O_2] \qquad (34)$$

Competition experiments between H^+ and H_2O_2 for the inorganic products from decomposition of α-phenylethyl(aquo)cobaloxime were based on the values of k^H_{app} and $k_{H_2O_2}$.

The redox reaction between $Co(dmgH)_2(OH_2)$ and $Co(NH_3)_5Br^{2+}$, results in the transfer of the halide, as shown in Equation 35 (24).

$$Co(NH_3)_5Br^{2+} + Co(dmgH)_2(OH_2) \xrightarrow{k_{CoBr^{2+}}} Co_{aq}^{2+} + Co(dmgH)_2(OH_2)Br + 5\ NH_3 \qquad (35)$$

The reaction proceeds by an inner-sphere mechanism with the second-order rate constant, $k_{CoBr^{2+}}$, equal to $(3.2 \pm 0.3) \times 10^5\ M^{-1}\ s^{-1}$ and independent of $[H^+]$. Kinetic data followed the second-order rate expression in Equation 36.

$$-d[Co(dmgH)_2(OH_2)]/dt = k_{CoBr^{2+}}[Co(dmgH)_2(OH_2)][Co(NH_3)_5Br^{2+}] \qquad (36)$$

When α-phenylethyl(aquo)cobaloxime was reacted in separate experiments with H_2O_2 and $Co(NH_3)Br^{2+}$ in acidic solution, linear pseudo-first-order plots were obtained. The values of k_{obs} in the presence of an excess amount of oxidant were virtually identical to values obtained with acid alone. Figure I-14 shows the independence of k_{obs} on the presence of oxidant. There is, consequently, no direct reaction between either oxidant and α-phenylethyl(aquo)cobaloxime.

Competition studies in the presence of H_2O_2

The inorganic products from the decomposition of α-phenylethyl-(aquo)cobaloxime in the presence of H^+ and H_2O_2 were analyzed quantitatively. In Scheme I-3 are outlined the competing reactions of H_2O_2 and H^+ with $Co(dmgH)_2(OH_2)$ and $HCo(dmgH)_2(OH_2)$ following homolysis and β-elimination of α-phenylethyl(aquo)cobaloxime. The two-electron oxidation of hydridocobaloxime by H_2O_2 and reaction with acid are relatively slow processes compared to the one-electron oxidation of $HCo(dmgH)_2(OH_2)$ by H_2O_2. Based on the study of hydridocobaloxime with acid (30) and the acid concentrations used in the competition experiments, $(0.60 - 1.99) \times 10^{-3}$ M, the range of pseudo-first-order rate constants for reaction of hydridocobaloxime with H^+ is $(0.43 - 1.23) \times 10^{-3}$ s^{-1}.

The one-electron oxidation of $HCo(dmgH)_2(OH_2)$ by H_2O_2 immediately converts it to $Co(dmgH)_2(OH_2)$ and competition is considered only between H^+ and H_2O_2 for reaction with $Co(dmgH)_2(OH_2)$. The following rate expressions are in accordance with Scheme I-3 (Equations 37-39).

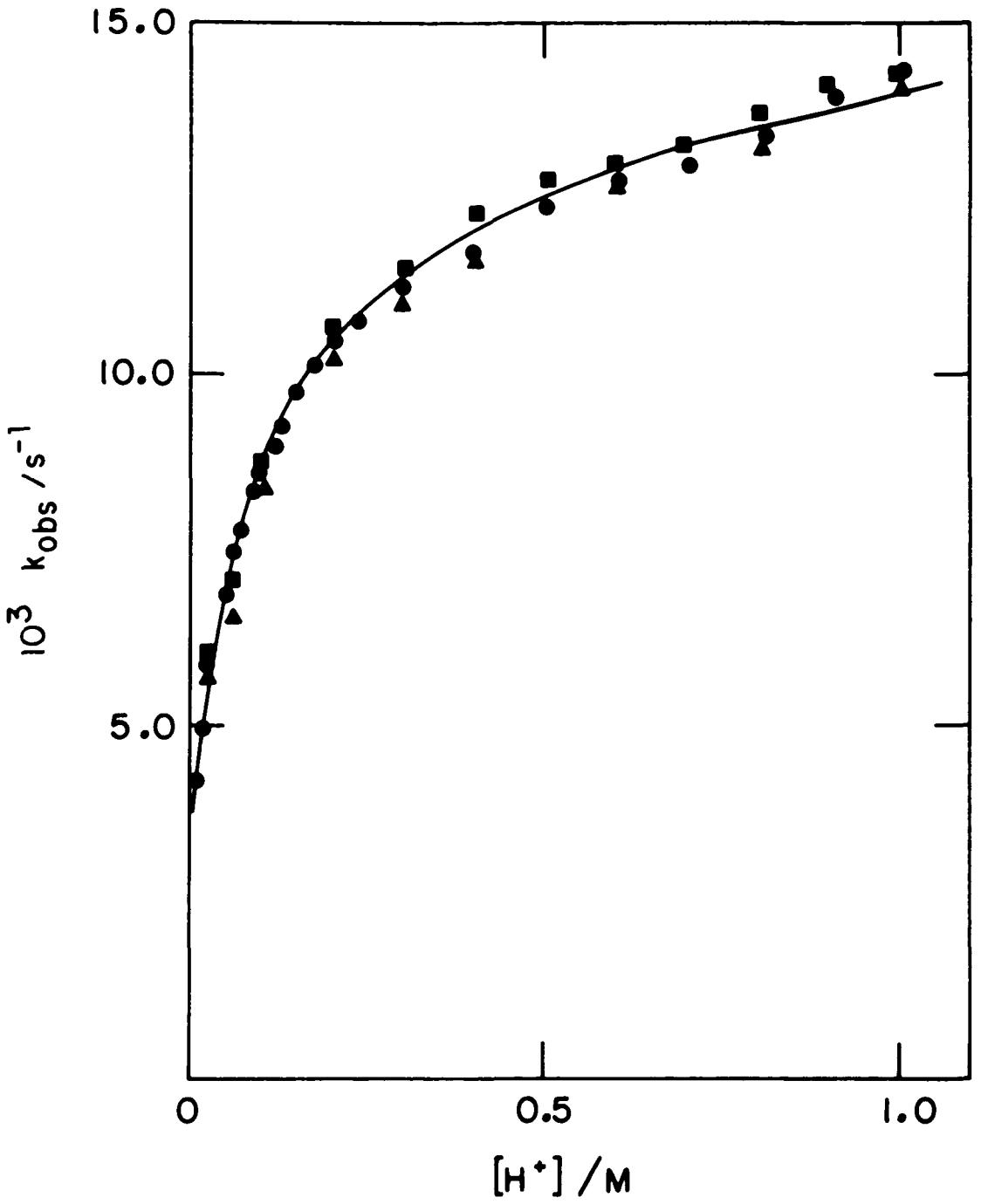
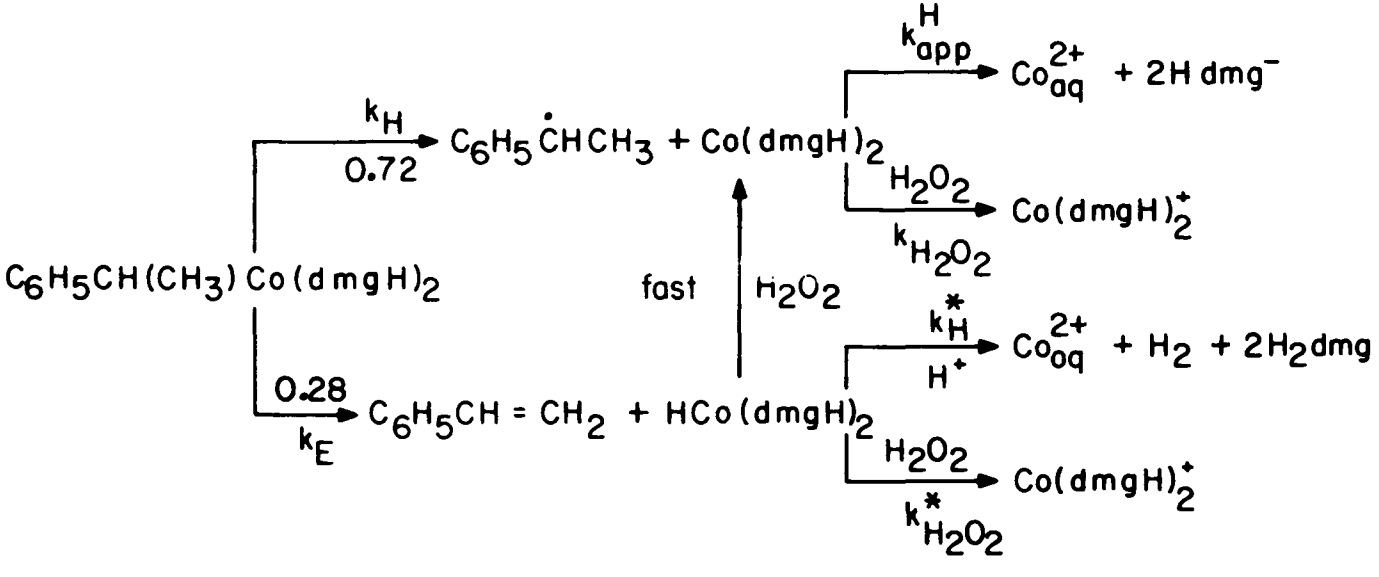


Figure I-14. Plot of k_{obs} vs. $[H^+]$ for the decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in the presence of H_2O_2 (triangles); $Co(NH_3)_5Br^{2+}$ (squares); H^+ (circles)

Scheme I-3


$C_6H_5CH(CH_3)Co(dmgH)_2$
k_H
0.72
$C_6H_5\dot{C}HCH_3 + Co(dmgH)_2$
k^H_{app}
$Co^{2+}_{aq} + 2H\,dmg^-$
H_2O_2
$k_{H_2O_2}$
$Co(dmgH)_2^+$
fast
H_2O_2
0.28
k_E
$C_6H_5CH=CH_2 + HCo(dmgH)_2$
k^*_H
H^+
$Co^{2+}_{aq} + H_2 + 2H_2dmg$
H_2O_2
$k^*_{H_2O_2}$
$Co(dmgH)_2^+$

$$-d[RCo(dmgH)_2(OH_2)]/dt = (k_H + k_E)\,[RCo(dmgH)_2(OH_2)] \quad (37)$$

$$d[Co_{aq}^{2+}]/dt = k_H\,[RCo(dmgH)_2(OH_2)] \times f + k_E\,[RCo(dmgH)_2(OH_2)] \times f \quad (38)$$

where $f = \dfrac{k_{app}^{H}}{k_{app}^{H} + k_{H_2O_2}[H_2O_2]}$

$$-d[RCo(dmgH)_2(OH_2)]/d[Co_{aq}^{2+}] = 1/f \quad (39)$$

The relationship between the reactants and the products is given by Equation 40, derived by integration of Equation 39 over the usual limits of constant $[H^+]$ and $[H_2O_2]$.

$$[RCo(dmgH)_2(OH_2)]/[Co_{aq}^{2+}] = 1/f = 1 + \frac{k_{H_2O_2}[H_2O_2]}{k_{app}^{H}} \quad (40)$$

The product data are given in Table I-9. A plot of $[RCo(dmgH)_2(OH_2)]_o/[Co_{aq}^{2+}]_\infty$ *vs.* $[H_2O_2]/k_{app}^{H}$ is shown in Figure I-15. A computer nonlinear least squares analysis of the product data results in an intercept of 0.97 ± 0.07 and a slope of $(1.94 \pm 0.09) \times 10^3$. The value of the slope is in excellent agreement with the independently measured second-order rate constant for reaction of $Co(dmgH)_2(OH_2)$ with H_2O_2, $(1.92 \pm 0.20) \times 10^3\ s^{-1}\ M^{-1}$ (39). These competition experiments are consistent with the proposed mechanism for decomposition of α-phenylethyl(aquo)cobaloxime involving both homolytic cobalt-carbon bond cleavage and β-elimination.

Table I-9. Products resulting from H^+ and H_2O_2 competition

$10^6[RCo(dmgH)_2]_o$/M	$[H_2O_2]$/M	$10^3[H^+]$/M	$10^6[Co_{aq}^{2+}]$/M	$10^6[Co(dmgH)_2^+]$/M	$\frac{[RCo(dmgH)_2]_o}{[Co_{aq}^{2+}]}$/M	$10^4 \frac{[H_2O_2]}{k_{app}^H}$
19.6	0.10	1.99	17.8	1.81	1.10	0.69
5.35	0.15	0.99	3.47	1.88	1.54	3.57
14.9	0.10	1.49	11.9	3.00	1.25	1.18
5.82	0.08	0.60	2.86	2.96	2.03	5.33
5.34	0.15	0.60	1.80	3.54	2.96	10.0
4.85	0.20	0.60	1.38	3.47	3.51	13.3

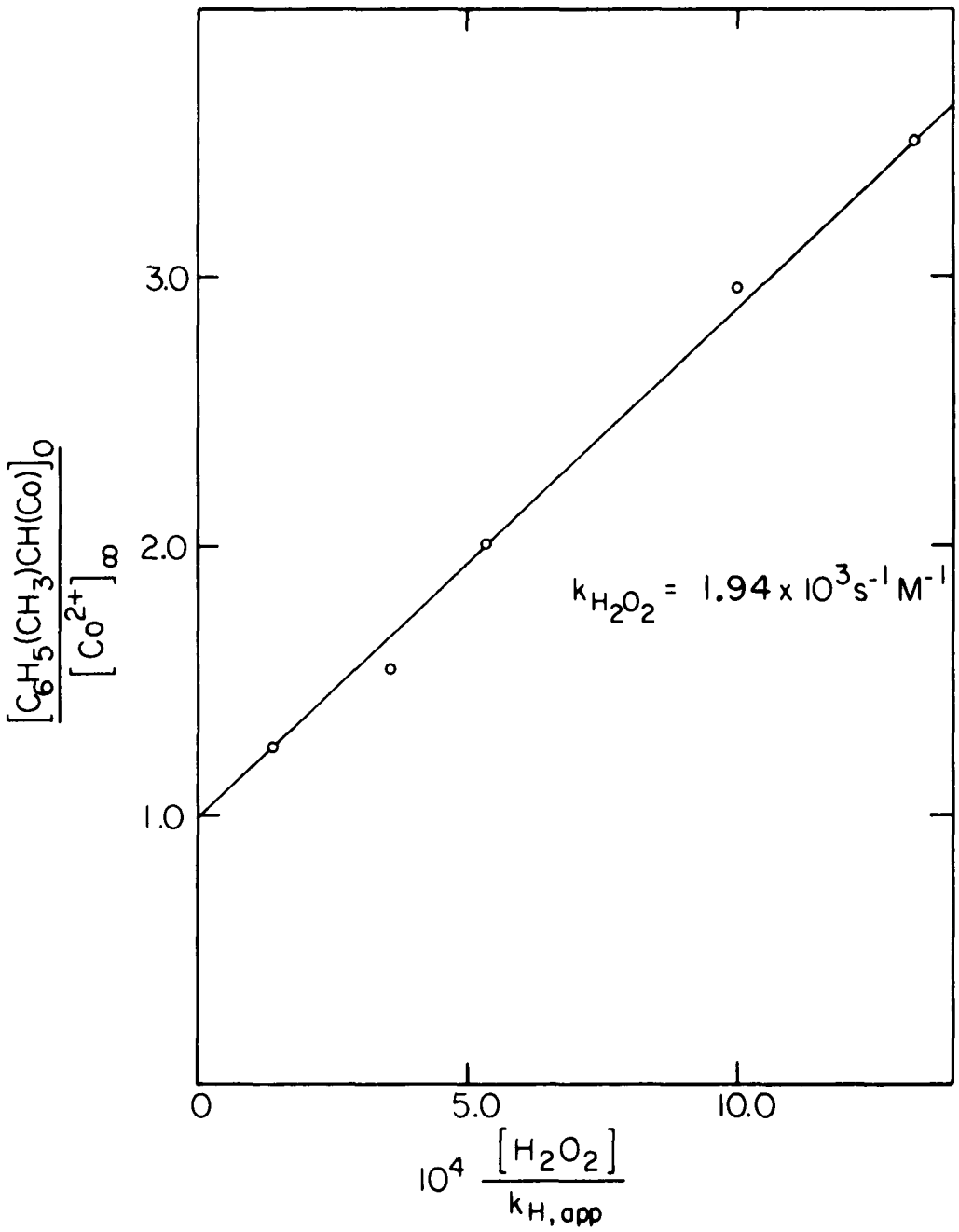


Figure I-15. Plot of $[RCo(dmgH)_2(OH_2)]/[Co_{aq}^{2+}]$ vs. $[H_2O_2]/k_{app}^{H}$ for the competing reactions of acid and H_2O_2 and Co_{aq}^{2+}

Competition studies in the presence of $Co(NH_3)_5Br^{2+}$

A similar competition study was carried out between acid and $Co(NH_3)_5Br^{2+}$ for reaction with the inorganic decomposition products of α-phenylethyl(aquo)cobaloxime. The product of β-elimination, $HCo(dmgH)_2(OH_2)$, was found to react very rapidly with $Co(NH_3)_5Br^{2+}$, much faster than the reaction between $HCo(dmgH)_2(OH_2)$ and low acid concentrations. In Scheme I-4 are postulated the reactions which are occurring for a system containing α-phenylethyl(aquo)cobaloxime, H^+, and $Co(NH_3)_5Br^{2+}$. In Table I-10 are the results of two competition reactions.

Based on the data given in the first line of Table I-10, a typical calculation will be illustrated for the amount of $BrCo(dmgH)_2(OH_2)$ formed during each decomposition process, homolysis and β-elimination. The value of k^H_{app} is 4170 s^{-1} at $[H^+] = 3.68 \times 10^{-3}$, $k_{CoBr^{2+}} = (3.2 \pm 0.3) \times 10^5\ M^{-1}\ s^{-1}$ (24).

The theoretical amount of $BrCo(dmgH)_2(OH_2)$ formed during homolysis should be:

$$[BrCo(dmgH)_2(OH_2)]_H = 0.72 \times \left[[RCo(dmgH)_2]_o \times \frac{k_{CoBr^{2+}}[Co(NH_3)_5Br^{2+}]}{k_{CoBr^{2+}}[Co(NH_3)_5Br^{2+}] + k^H_{app}} \right]$$

$$= 5.74 \times 10^{-5}\ M$$

Scheme I-4

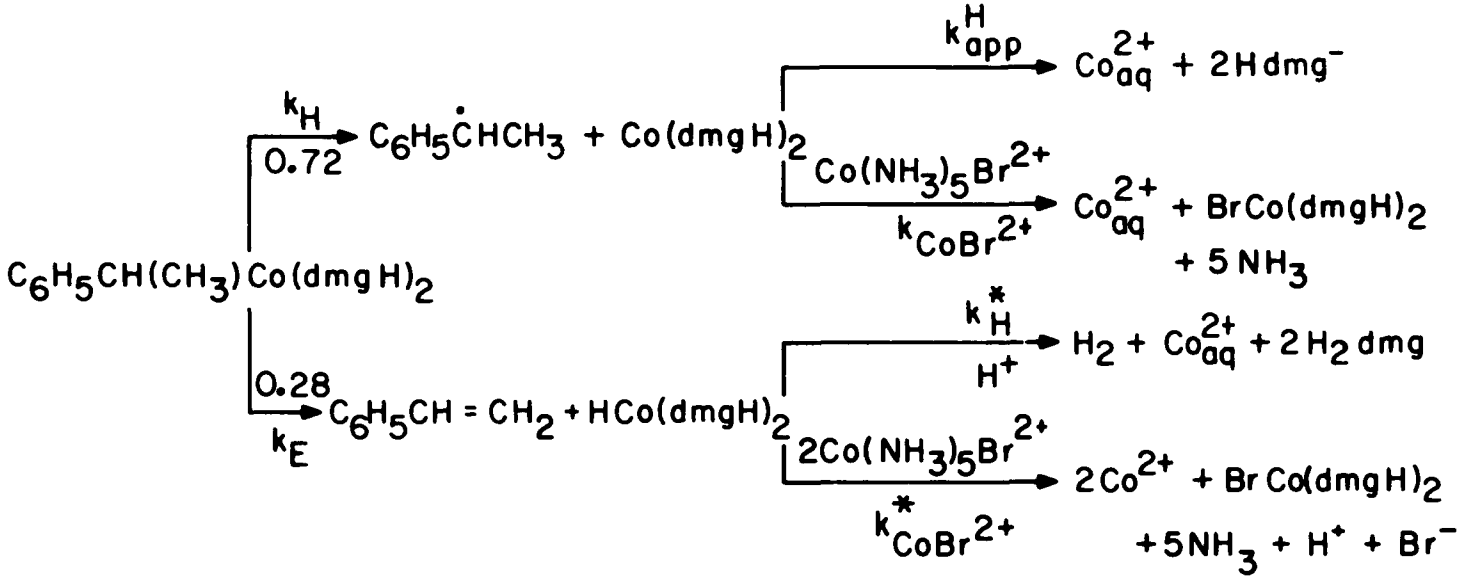

$C_6H_5CH(CH_3)Co(dmgH)_2$
k_H
0.72
$C_6H_5\dot{C}HCH_3 + Co(dmgH)_2$
k^H_{app}
$Co^{2+}_{aq} + 2Hdmg^-$
$Co(NH_3)_5Br^{2+}$
$k_{CoBr^{2+}}$
$Co^{2+}_{aq} + BrCo(dmgH)_2 + 5NH_3$
0.28
k_E
$C_6H_5CH=CH_2 + HCo(dmgH)_2$
k^*_H
H^+
$H_2 + Co^{2+}_{aq} + 2H_2dmg$
$2Co(NH_3)_5Br^{2+}$
$k^*_{CoBr^{2+}}$
$2Co^{2+} + BrCo(dmgH)_2 + 5NH_3 + H^+ + Br^-$

Table I-10. Products resulting from H^+ and $Co(NH_3)_5Br^{2+}$ competition

$10^4[RCo(dmgH)_2]_o$/M	$10^3[Co(NH_3)_5Br^{2+}]$/M	$10^3[H^+]$/M	$10^4[BrCo(dmgH)_2]^a$/M	$10^4[Co_{aq}^{2+}]_\infty$/M
3.64	3.65	3.68	1.99	3.19
2.72	2.73	2.73	1.59	2.43

[a]Separated on SP Sephadex-C25 cation exchange resin.

The observed $[BrCo(dmgH)_2(OH_2)]_{total}$ is 1.99×10^{-4} M, so the actual amount of $BrCo(dmgH)_2(OH_2)$ formed during β-elimination is $[BrCo(dmgH)_2(OH_2)]_E = 1.42 \times 10^{-4}$ M. To check whether the actual $[BrCo(dmgH)_2(OH_2)]_E$ is consistent with the proposed Scheme I-4, the theoretical amount of $[BrCo(dmgH)_2(OH_2)]_E$ was calculated.

$$[BrCo(dmgH)_2(OH_2)]_E = 0.28 \times \left[[RCo(dmgH)_2]_o \times \frac{k^*_{CoBr^{2+}}[Co(NH_3)_5Br^{2+}]}{k^*_{CoBr^{2+}}[Co(NH_3)_5Br^{2+}] + k^*_H[H^+]} \right]$$

At $[H^+] = 3.68 \times 10^{-3}$ M, $k^*_H[H^+]$ is 1.94×10^{-3} (18), and this relation is true: $k^*_{CoBr^{2+}}$ $(3.65 \times 10^{-3}) >> 1.94 \times 10^{-3}$. The theoretical amount of $[BrCo(dmgH)_2(OH_2)]_E$ reduces to $[BrCo(dmgH)_2]_E = 0.28 \times 3.64 \times 10^{-4} = 1.02 \times 10^{-4}$ M. The difference between the actual and the calculated amounts of $BrCo(dmgH)_2(OH_2)$ may be due to a systematic experimental error, bleeding of Co^{2+}_{aq} from the cation-exchange column into the eluting bromo(aquo)cobaloxime.

Decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ with Cu^{2+}

When α-phenylethyl(aquo)cobaloxime was reacted with Cu^{2+} in acidic solution under pseudo-first-order conditions, the rate of decomposition was more rapid than the reaction with acid alone. For instance, at 0.01 M H^+, k_{obs} is 1.1×10^{-2} s^{-1} in the presence of Cu^{2+} and 4.2×10^{-3} s^{-1} in its absence. The total decrease in absorption at 368 nm was approximately one-half as large as typical absorbance changes for decomposition of α-phenylethyl(aquo)cobaloxime. The final

product spectrum was identical to the UV-visible spectrum of an alkylcobaloxime, all of which are quite similar, and was stable over long periods of time in the absence of oxygen. The implication of these experiments is that α-phenylethyl(aquo)cobaloxime is converted in the presence of Cu^{2+} to a much stabler organocobaloxime.

We might suggest in view of the production of a stable alkylcobaloxime, and therefore definitely not the starting material, that Cu^{2+} promotes rearrangement to β-phenylethyl(aquo)cobaloxime. The rate-limiting step for the oxidation of alkyl radicals by Cu^{2+} has been shown to involve formation of an organocopper intermediate which subsequently undergoes substitution and elimination reactions (40). One argument concerning the decomposition of α-phenylethyl(aquo)cobaloxime in the presence of Cu^{2+} might invoke formation of an organocopper complex which reacts with hydridocobaloxime. Addition of $HCo(dmgH)_2(OH_2)$ to the organocopper complex in a concerted manner with displacement of Cu(I) could result in β-phenylethyl(aquo)cobaloxime (Equations 41-42).

$$Cu^{2+} + C_6H_5\dot{C}HCH_3 \rightleftharpoons CuCH(CH_3)C_6H_5^{2+} \qquad (41)$$

$$CuCH(CH_3)C_6H_5^{2+} + HCo(dmgH)_2(OH_2) \longrightarrow \left[Cu\cdots \underset{\displaystyle H\cdots CH_2}{\overset{\displaystyle C_6H_5}{C}} -H \; H-Co(dmgH)_2(OH_2) \right]^{\ddagger}$$

$$\longrightarrow Cu^{+} + H^{+} + C_6H_5CH_2CH_2Co(dmgH)_2(OH_2) \qquad (42)$$

Kinetics for the Reaction of $C_6H_5CH(CH_3)(dmgH)_2(OH_2)$ with Fe^{3+}

The decomposition of α-phenylethyl(aquo)cobaloxime in acidic solution containing Fe^{3+} was monitored at 464 nm. Pseudo-first-order plots of ln $(D_t - D_\infty)$ *vs.* time were linear, and the data collected are tabulated in Table I-11. The values of k_{obs} at constant acid concentration are approximately three times higher than 8.56×10^{-3} s^{-1}, the pseudo-first-order rate constant for decomposition at $[H^+] = 0.10$ M. The rate of reaction is clearly dependent on $[Fe^{3+}]$, albeit a non-linear dependence.

Table I-11. Rate constants for the reaction of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ with Fe^{3+}[a]

$10^4[RCo(dmgH)_2]_o$/M	$[Fe^{3+}]$/M	$10^2 k_{obs}/s^{-1}$
10.1	0.010	2.03
5.91	0.025	2.16
7.66	0.050	2.28
5.91	0.075	3.04

[a] T = 25°C; $[H^+] = 0.10$ M.

These preliminary results are indicative of adduct formation between Fe^{3+} and the bis(dimethylglyoxime) macrocycle of the organocobaloxime. Earlier studies have shown that Fe^{3+} undergoes a

reversible association with methyl(aquo)cobaloxime and with diaquo-cobaloxime in which Fe^{3+} replaces the hydrogen-bonded proton in one O — H - - - O group of the parent cobaloxime (41). This same type of complexation is probably occurring between α-phenylethyl(aquo)cobaloxime and Fe^{3+} as illustrated in Equation 43.

$$C_6H_5CH(CH_3)Co(dmgH)_2(OH_2) + Fe^{3+} = C_6H_5CH(CH_3)Co(dmg_2HFe)(OH_2)^{2+} + H^+ \quad (43)$$

The complexity of the rate law for adduct formation between Fe^{3+} and an organocobaloxime (41) accounts for the curvature of a plot of k_{obs} *vs.* $[Fe^{3+}]$.

Decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in Neutral Solution

Confirmation of the value of k_b

The first-order rate constant for the decomposition of the unprotonated α-phenylethyl(aquo)cobaloxime, k_b, was determined as $(3.55 \pm 0.07) \times 10^{-3}$ s^{-1} in acidic solution by fitting the values of k_{obs} to a function of $[H^+]$, as described earlier. The value of k_b can be measured directly in neutral solution where k_{obs} should be equal to k_b. In the presence of a scavenger at pH ∿ 7, a more accurate comparison can be made between k_b in 40% v/v methanol/water and in toluene, the solvent chosen by Halpern *et al.* for decomposition of α-phenylethyl(py)cobaloxime (17). Determinations were done using $Co(NH_3)_5Br^{2+}$ or O_2 in neutral solution to react rapidly with any

$Co(dmgH)_2(OH_2)$ and $HCo(dmgH)_2(OH_2)$ formed, thereby drawing the decomposition reactions to completion.

Decomposition in the presence of $Co(NH_3)_5Br^{2+}$

Kinetic data are given in Table I-12 for the decomposition of α-phenylethyl(aquo)cobaloxime in the presence of $Co(NH_3)_5Br^{2+}$ at pH ∿ 7. Linear pseudo-first-order plots of ln $(D_t - D_\infty)$ *vs.* time were obtained. The average value of k_{obs}, $(3.27 \pm 0.21) \times 10^{-3}$ s^{-1}, agree with the value of k_b measured under different reaction conditions. In toluene, Halpern *et al.* found that k_{obs} (25°C) = 7.8×10^{-4} s^{-1} (17). The

Table I-12. Rate constants for decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in the presence of $Co(NH_3)_5Br^{2+}$[a]

$10^3[Co(NH_3)_5Br^{2+}]/M$	$10^3k_{obs}/s^{-1}$
1.33	3.34
2.62	3.58
5.28	3.03
6.10	3.27
7.39	3.14

[a] T = 25.0°C; pH ∿ 7; μ = 1.0 M ($LiClO_4$); $[C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)] = 1 \times 10^{-5}$ M.

difference in the polarities of the two solvents possibly accounts for the factor of four in the values of k_{obs}.

Decomposition in the presence of oxygen

The decomposition of α-phenylethyl(aquo)cobaloxime was carried out in neutral solution with oxygen present. The approximate concentration of oxygen was 1×10^{-3} M and $[C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)]_o = 1 \times 10^{-5}$ M. The first-order rate constant was $(3.16 \pm 0.01) \times 10^{-3}$ s^{-1}. This value of k_b is in agreement with k_b measured in the presence of $Co(NH_3)_5Br^{2+}$. A better assessment of the kinetic data shows that $(3.27 \pm 0.21) \times 10^{-3}$ s^{-1} for k_b is the most accurate value.

Decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in the Presence of $Co(en)_3^{3+}$

Kinetics

In neutral solution, a mass law retardation effect on the rate of decomposition of α-phenylethyl(aquo)cobaloxime was observed in the presence of tris(ethylenediamine)cobalt(III), $Co(en)_3^{3+}$. Tris-(ethylenediamine)cobalt(III) is unreactive toward $Co(dmgH)_2(OH_2)$, produced during homolysis of α-phenylethyl(aquo)cobaloxime, and accumulation in the system leads to a significant back reaction of the α-phenylethyl radical with $Co(dmgH)_2(OH_2)$.

Tris(ethylenediamine)cobalt(III) was the only oxidizing agent studied that might selectively react with the organic radical. Benzyl radicals are not oxidized by $Co(en)_3^{3+}$ (42), but the greater reactivity of α-phenylethyl radicals should increase the possibility of oxidation.

Consumption of the organic radical by $Co(en)_3^{3+}$ is expected to be slower than the reverse reaction with $Co(dmgH)_2(OH_2)$. The other scavengers studied, H^+, H_2O_2, and $Co(NH_3)_5Br^{2+}$, react with sufficiently high rates under pseudo-first-order conditions with $Co(dmgH)_2(OH_2)$ that the back reaction is virtually negligible. In the presence of $Co(en)_3^{3+}$, a direct competition between $Co(dmgH)_2(OH_2)$ and the oxidant for reaction with α-phenylethyl radical is expected. The reaction of $Co(en)_3^{3+}$ with hydridocobaloxime, produced during β-elimination of α-phenylethyl(aquo)-cobaloxime, is very rapid.

Linear pseudo-first-order plots of ln $(D_t - D_\infty)$ *vs.* time were obtained for the decomposition of the organocobaloxime in neutral solution containing $Co(en)_3^{3+}$. The kinetic data are given in Table I-13. The average value of $[Co(dmgH)_2]/[Co(en)_3^{3+}]$ comes about because of the uncertainty in $[Co(dmgH)_2(OH_2)]$ during a kinetic run; it is continually being generated from the decomposition of α-phenylethyl(aquo)cobaloxime in the system. The range in concentrations represents the original and final concentrations of $[Co(dmgH)_2(OH_2)]$ and is known with fairly good accuracy. It is clear from the data in Table I-13 that the k_{obs} values are much lower than k_b, $(3.27 \pm 0.21) \times 10^{-3}$ s^{-1}, for varying concentrations of organocobaloxime and $Co(en)_3^{3+}$.

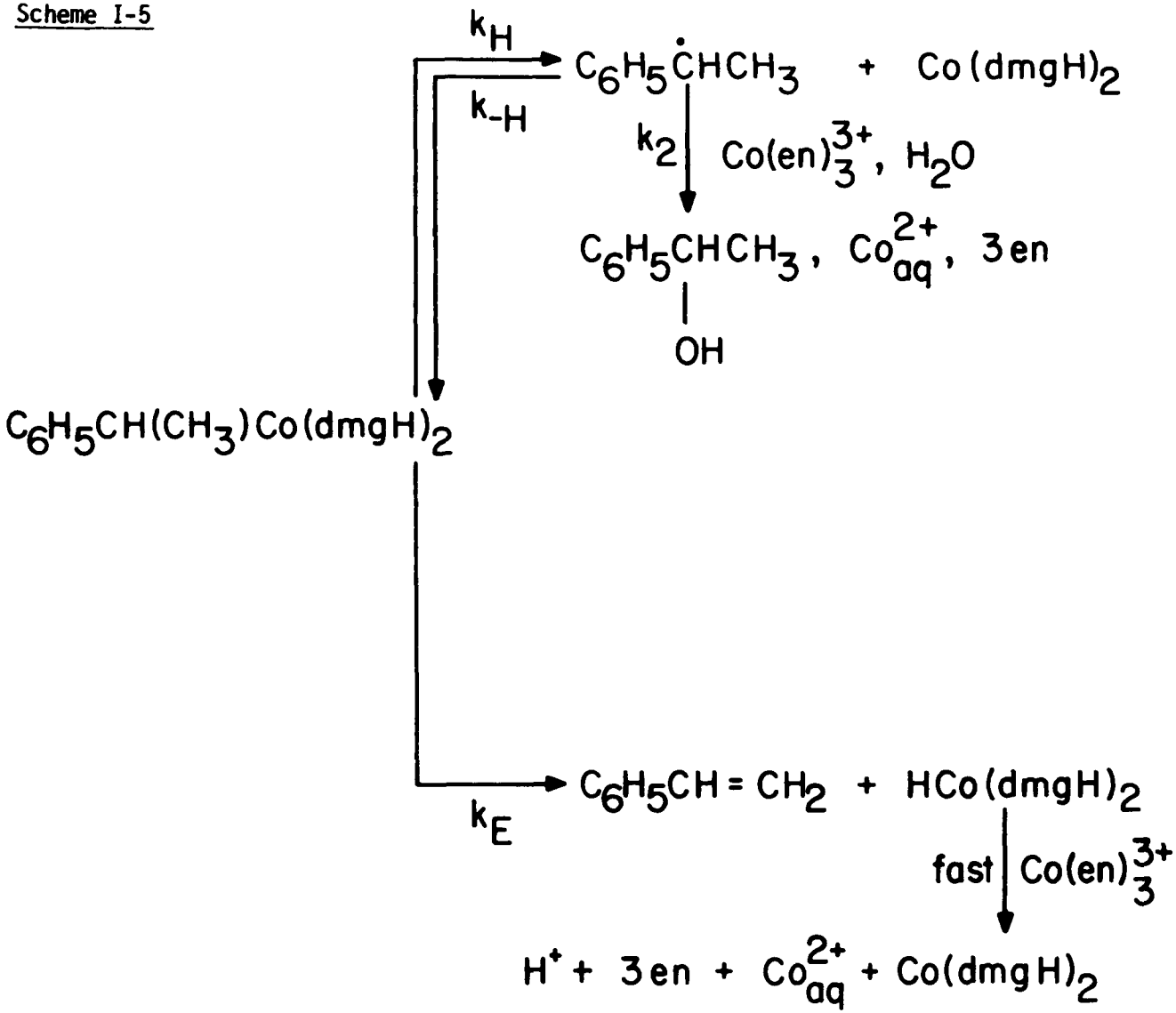
Scheme I-5 is postulated to illustrate the kinetic results. For the homolytic pathway, recombination of α-phenylethyl radical with $Co(dmgH)_2(OH_2)$ is an important reaction. Equation 44 applies to the homolytic decomposition:

Table I-13. Kinetic data for the decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in the presence of $Co(en)_3^{3+a}$

$10^4[Co(dmgH)_2]/M$	$10^3[Co(en)_3^{3+}]/M$	$10^2\frac{[Co(dmgH)_2]}{[Co(en)_3^{3+}]}$	$10^2\frac{[Co(dmgH)_2]}{[Co(en)_3^{3+}]}$	$10^3k_{obs}/s^{-1}$
Range		Range	Average	
1.04 - 1.49	11.9	0.87 - 1.2	1.1	1.0
0.59 - 1.14	5.95	0.99 - 1.9	1.5	0.98
0.11 - 0.17	5.95	1.9 - 2.9	2.4	0.95
2.11 - 2.45	4.69	4.5 - 5.2	4.9	0.86
2.46 - 3.52	5.10	4.8 - 6.9	5.9	0.81
2.06 - 2.52	3.35	6.1 - 7.5	6.8	0.80
3.07 - 6.58	4.09	7.5 - 8.6	8.1	0.76

[a] $T = 25.0°C$; $\mu = 1.0$ M ($LiClO_4$).

Scheme I-5


k_H
k_{-H}
$C_6H_5\dot{C}HCH_3$ + $Co(dmgH)_2$
k_2 $Co(en)_3^{3+}$, H_2O
$C_6H_5CHCH_3$, Co_{aq}^{2+}, 3en
OH
$C_6H_5CH(CH_3)Co(dmgH)_2$
$C_6H_5CH=CH_2$ + $HCo(dmgH)_2$
k_E
fast $Co(en)_3^{3+}$
H^+ + 3en + Co_{aq}^{2+} + $Co(dmgH)_2$

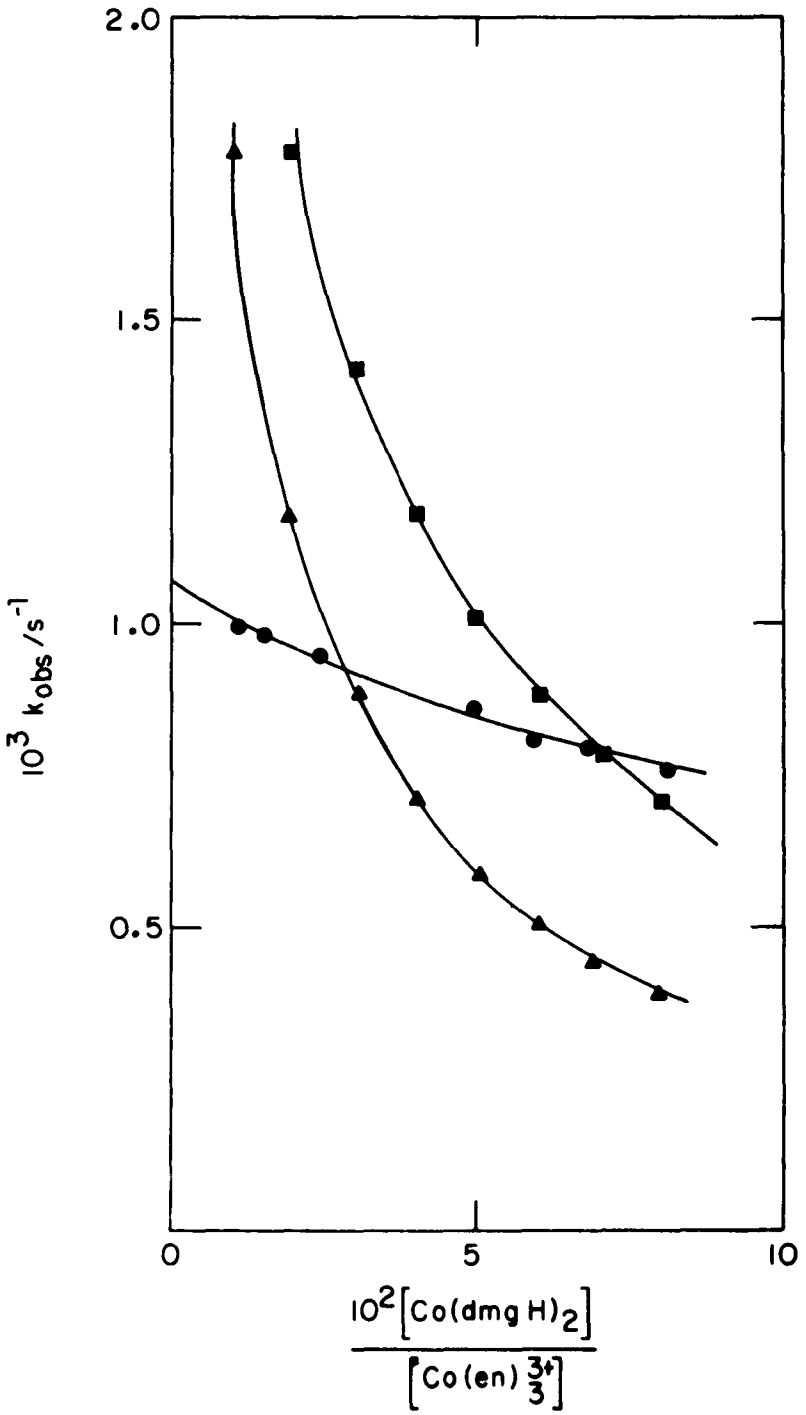
$$k_{obs} = \frac{k_H}{\frac{k_{-H}\,[Co(dmgH)_2]}{k_2\,[Co(en)_3^{3+}]} + 1} \qquad (44)$$

A plot of k_{obs} *vs.* $[Co(dmgH)_2]/[Co(en)_3^{3+}]$ is shown in Figure I-16. The two steepest curves are based on assignment of the ratio $\frac{k_{-H}}{k_2}$, values of 50 and 100 and $k_{-H} = k_b$. Only the homolytic pathway for decomposition of α-phenylethyl(aquo)cobaloxime is considered in this analysis. The actual data for k_{obs} *vs.* $[Co(dmgH)_2]/[Co(en)_3^{3+}$ imply that $\frac{k_{-H}}{k_2}$ is in the range 50 to 100, but assignment of $k_H = k_b$, the intercept of the plot in Figure I-16, is clearly incorrect. Not only does this study show that the second-order rate constant for recombination, k_{-H}, is greater than k_2, the second-order rate constant for reaction of $Co(en)_3^{3+}$ with the α-phenylethyl radical, but that the elimination pathway for decomposition is significant.

The back reaction of the β-elimination pathway is considered to be negligible due to the rapidity of the reaction of hydridocobaloxime with $Co(en)_3^{3+}$. When the β-elimination pathway is accounted for, k_{obs} takes the form in Equation 45.

$$k_{obs} = \frac{k_H}{\frac{k_{-H}\,[Co(dmgH)_2]}{k_2\,[Co(en)_3^{3+}} + 1} + k_E \qquad (45)$$

Figure I-16. Plot of k_{obs} vs. $[Co(dmgH)_2(OH_2)]/[Co(en)_3^{3+}]$ for homolytic decomposition of $C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)$ in the presence of $Co(en)_3^{3+}$ (circles); assuming $k_{-H}/k_2 = 50$ (squares); assuming $k_{-H}/k_2 = 100$ (triangles)


2.0
1.5
1.0
0.5
0
5
10
$10^3 k_{obs}/s^{-1}$
$\frac{10^2[Co(dmgH)_2]}{[Co(en)_3^{3+}]}$

Inorganic products

Cobalt analysis of the product solutions from the reaction of α-phenylethyl(aquo)cobaloxime with $Co(en)_3^{3+}$ under the same conditions as the kinetic runs resulted in $[Co_{aq}^{2+}]_\infty = 1.3 - 1.6\ [C_6H_5CH(CH_3)Co(dmgH)_2]_o$. Apparently, $Co(en)_3^{3+}$ is being consumed in this system. In acidic solution containing α-phenylethyl(aquo)cobaloxime and $Co(en)_3^{3+}$, the cobalt analysis resulted in $[Co_{aq}^{2+}] = [C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)]_o$. Since $Co(dmgH)_2(OH_2)$ is immediately coverted to Co_{aq}^{2+} in acidic solution, the organic radical formed by homolysis is unable to recombine with $Co(dmgH)_2(OH_2)$ and has the option of either undergoing dimerization or reacting with $Co(en)_3^{3+}$. Dimerization must occur because no $Co(en)_3^{3+}$ is consumed in the system, as shown by $[Co_{aq}^{2+}] = [C_6H_5CH(CH_3)Co(dmgH)_2(OH_2)]_o$. Likewise, $HCo(dmgH)_2(OH_2)$, produced during β-elimination, preferentially reacts with H^+ since no $Co(en)_3^{3+}$ is reduced.

Organic products

The organic products from the decomposition of α-phenylethyl(aquo)-cobaloxime in neutral solution containing $Co(en)_3^{3+}$ were analyzed semi-quantitatively by gas-liquid chromatography. Two control experiments were carried out and their organic products were analyzed as well. The first control was a neutral solution containing only α-phenylethyl(aquo)-cobaloxime, and the second consisted of α-phenylethyl(aquo)cobaloxime and $Co(en)_3^{3+}$ in acidic solution. These three experiments will be symbolized in this manner:

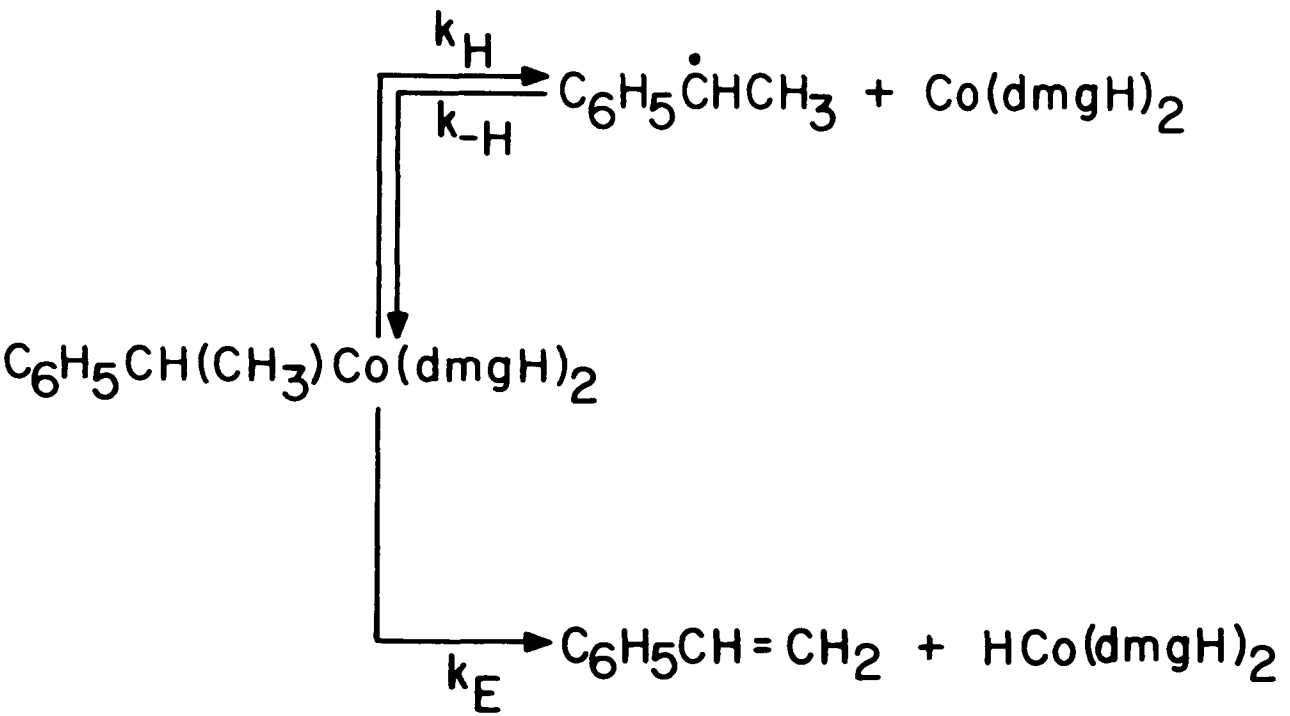
1. $RCo(dmgH)_2 + Co(en)_3^{3+}$
2. $RCo(dmgH)_2$
3. $RCo(dmgH)_2 + Co(en)_3^{3+} + H^+$

Styrene is found in the ratio 1:22:7 for experiments 1, 2, and 3, respectively. The four dimeric products are formed in large amounts only in experiment 3; they are not produced in experiments 1 and 2.

A strong indication that in neutral solution $Co(en)_3^{3+}$ competes efficiently with $Co(dmgH)_2(OH_2)$, for reaction with α-phenylethyl radicals, is that styrene is produced in relatively small amounts in experiment 1. Scheme I-5 represents the concurrent reactions in experiment 1. Based on the approximate steady-state concentration of 3×10^{-11} M for the α-phenylethyl radical generated during homolysis, the rate of recombination of $Co(dmgH)_2(OH_2)$ with the organic radical should be 3×10^{-7} s^{-1} M. Likewise, the rate of dimerization is expected to be 4×10^{-12} s^{-1} M. It is then understandable why dimerization does not occur in experiment 1.

β-Elimination and α-phenylethyl(aquo)cobaloxime is, in effect, the only decomposition pathway in experiment 2. Homolytic cleavage of the cobalt-alkyl bond occurs, but is immediately followed by recombination of the products because the rate of dimerization is several orders of magnitude slower than the recombination rate. Styrene and hydridocobaloxime accumulate in the system until all of the organocobaloxime is depleted. Experiment 2 is illustrated by Scheme I-6.

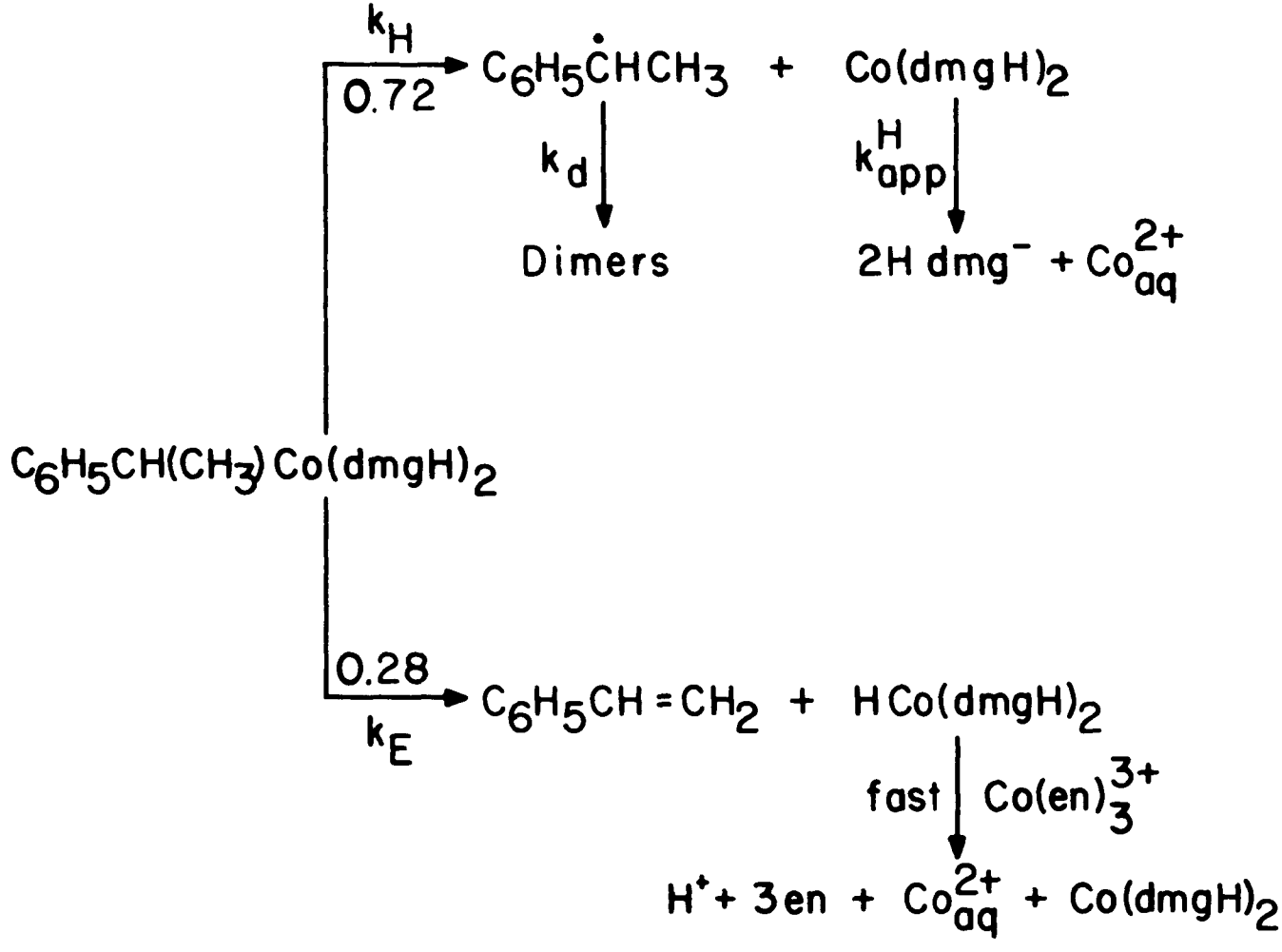
Scheme I-6


k_H
k_{-H}
$C_6H_5\dot{C}HCH_3 + Co(dmgH)_2$
$C_6H_5CH(CH_3)Co(dmgH)_2$
k_E
$C_6H_5CH=CH_2 + HCo(dmgH)_2$

In acidic solution, $Co(dmgH)_2(OH_2)$ upon formation is instantly removed from the system by H^+, and reversal of homolysis cannot happen. Seventy-two percent of α-phenylethyl(aquo)cobaloxime homolyzes and 28% undergoes β-elimination in experiment 3. Tris(ethylenediamine)-cobalt(III) is essentially unable to compete with dimerization of the α-phenylethyl radicals. The majority of the organic products, therefore, consists of the four dimeric compounds, and styrene accounts for the remainder. Scheme I-7 outlines the reactions in experiment 3.

In neutral solution containing $Co(en)_3^{3+}$, the rate of decomposition slows down as a result of the mass law retardation effect; however, the pH dependence on the product analysis is not clearly understood. More styrene would be expected from decomposition of α-phenylethyl(aquo)cobaloxime in the presence of $Co(en)_3^{3+}$ because of significant recombination of the homolytic products in neutral solution.

Scheme I-7


k_H
0.72
$C_6H_5\dot{C}HCH_3$ + $Co(dmgH)_2$
k_d
k^H_{app}
Dimers
$2H\,dmg^- + Co^{2+}_{aq}$
$C_6H_5CH(CH_3)Co(dmgH)_2$
0.28
k_E
$C_6H_5CH=CH_2$ + $HCo(dmgH)_2$
fast
$Co(en)_3^{3+}$
$H^+ + 3en + Co^{2+}_{aq} + Co(dmgH)_2$

CONCLUSIONS

Three viewpoints concerning the feasible modes for decomposition of α-phenylethyl(aquo)cobaloxime under anaerobic conditions have been proposed. The first concluded that β-elimination correctly describes the decomposition process, based on formation of styrene in the reaction mixture (16). The presence of styrene was substantiated by the Halpern et al. results, but it was argued that cobalt-carbon bond cleavage preceded styrene formation (17). Styrene, in their mechanism, occurred by hydrogen abstraction from the α-phenylethyl radical.

When the decomposition of this organocobaloxime is studied under various reaction conditions, it is discovered that both homolysis and β-elimination are realistic interpretations of the kinetic and product analysis data. It is possible to reconcile somewhat all three proposals, if the reaction conditions and the scavengers present in the system are strictly defined. In other words, the decomposition of α-phenylethyl-(aquo)cobaloxime is governed by its immediate surroundings.

A situation where 72% of α-phenylethyl(aquo)cobaloxime decomposes by homolytic cobalt-carbon bond cleavage and 28% by β-elimination occurs in a system containing scavengers for $Co(dmgH)_2(OH_2)$, the inorganic product of homolysis. These scavengers are typically acid or oxidants, such as H_2O_2 and $Co(NH_3)_5X^{2+}$. Homolysis in acidic solution is verified by radical coupling products which account for 72% of the total organic products. The remaining organic products are derived from β-elimination.

The organic product distribution is completely altered when these scavengers are absent or only a weak oxidant, such as $Co(en)_3^{3+}$, is

present which may selectively react with the α-phenylethyl radical. When efficient scavengers are not present, recombination of the organic radical with $Co(dmgH)_2(OH_2)$ is a major reaction. Cobalt-carbon bond cleavage continues, but the back reaction immediately restores the products to the original organocobaloxime. The reaction of styrene with hydrido(aquo)cobaloxime, the inorganic product of β-elimination, is relatively slow and in the absence of a scavenger, the back reaction for β-elimination is unimportant. Styrene is the only organic product formed in the absence of scavengers; a mixture of styrene and the organic oxidation product occurs when $Co(en)_3^{3+}$ is present.

The original experiments (16) on α-phenylethyl(py)cobaloxime's decomposition took place in acetone or chloroform solutions containing no scavenger. Under these conditions, β-elimination is, in effect, the only pathway for decomposition, and homolysis is virtually a chemical "dead-end". Styrene is the only organic product that would be expected.

The same conditions apply to the experiments done in toluene by Halpern and co-workers (17). β-Elimination would be the predominant mode of decomposition under their reaction conditions and, as expected, styrene is the only organic product detected. Halpern et al. propose that homolysis can account for the styrene produced, although the small value of $\Delta S^{\ddagger}$ they obtain in toluene does not support this kind of mechanism.

These studies inevitably lead to the question: is the mode for decomposition of α-phenylethyl(aquo)cobaloxime unique, or are the pathways for decomposition of all unstable organocobaloximes dictated

by the particular reaction conditions? The reactivity of α-phenylethyl-(aquo)cobaloxime is not only a function of the steric bulk imposed by the α-phenylethyl group, but also of the availability of a β-hydrogen atom. This organocobaloxime is peculiar in that it actually has two alternative routes for decomposition. In addition, α-phenylethyl-(aquo)cobaloxime is so unstable that external effects easily shift the direction for decomposition.

Other organocobaloximes with the same choices for decomposition would probably react similarly. The small number of unstable organocobaloximes that have been synthesized would be expected, however, to have a preferred mode of decomposition, independent of the scavengers present in the system.

Presently, other organocobalt compounds have not yet been found which undergo both homolytic cobalt-carbon bond cleavage and intramolecular β-hydrogen elimination reactions. The concurrent decomposition routes for α-phenylethyl(aquo)cobaloxime are, therefore, significant in the context of organometallic chemistry.

PART II. SINGLE-ELECTRON REDUCTION OF CHROMIUM(III) COMPLEXES BY VITAMIN B_{12s}

INTRODUCTION

Vitamin B_{12s} is a cobalt(I) corrin complex, also known as cob(I)-alamin, having a formula abbreviated as $[Co^{I}]^{-}$. Other derivatives are vitamins B_{12r} and B_{12a} (aquocobalamin), $[Co^{II}]$ and $[Co^{III}]^{+}$, respectively, and organometallic derivatives such as alkylcobalamins are referred to as R[Co].

The Co(II)/(Co(I) reduction potentials of vitamin B_{12} are a function of pH and have been found to range from -0.851 V vs. SCE above pH 4.7 to -0.740 V vs. SCE at pH 2.9 (43-45).

The spin-paired d^{8} Co(I) ion in vitamin B_{12s} is four coordinate with a square planar configuration (1). The highest occupied orbital in the reduced cobalt species is the weakly antibonding $d_{z}2$ orbital (7, 46), whose directional characteristics and high charge density are responsible for the high nucleophilicity perpendicular to the plane of the molecule.

B_{12s} is a powerful nucleophile toward organic halides (RX) (Equation 46) in which the reaction proceeds by an $S_{N}2$ mechanism (47).

$$[Co^{I}]^{-} + RX \longrightarrow R[Co] + X^{-} \qquad (46)$$

Vitamin B_{12s} reactions with alkylating agents are not subject to greater steric hindrance than those of cobaloximes, and, in fact, of simple nucleophiles such as iodide ion. This is remarkable, as the alkylcobalamins, which should form in the reactions with secondary alkyl halides, are unstable, decomposing into B_{12r} and olefin, but most corresponding cobaloximes can be isolated.

Corrinoids which possess a Co-C bond can also be formed by ring-opening and addition reactions (1) (Equations 47 and 48).

$$[Co^{I}]^{-} + \underset{\diagup \quad \diagdown}{\overset{O}{CH_2CH_2}} + H^{+} \longrightarrow [Co\text{-}CH_2CH_2OH] \qquad (47)$$

$$[Co^{I}]^{-} + H\text{-}C{\equiv}C\text{-}H + H^{+} \longrightarrow [Co\text{-}CH{=}CH_2] \qquad (48)$$

At one time, it was considered that B_{12s} was a cobalt(III)hydride, i.e., hydridocobalamin, because it was able to add to multiple bonds as in Equation 48 and to react with diazomethane to give methylcobalamin. It is now known that B_{12s} is simply cobalamin-cobalt(I) over the pH range 2.9-15 (43-45). If the addition reactions (Equation 48) occurred via the intermediate formation of the cobalt(III)hydride, the rate of addition would increase rapidly with a fall in pH. No pH dependence has yet been reported for any of these reactions. It is reasonable to conclude that reactions 46-48 all involve the $[Co^{I}]$ complex and that the rate-determining step is the formation of the Co-C bond, followed by the very rapid uptake of a proton.

The nucleophilicity of $[Co^{I}]^{-}$ has been extensively studied (1, 48) because of its importance in the synthesis of organocobalamins (11, 49) and in enzymatic reactions (50-51).

On the other hand, only a limited amount of work has been done on the reactivity of B_{12s} as a powerful one-electron reducing agent. Earlier studies involving the transfer of an electron between B_{12s} and aquocobalamin was first reported by Hill and coworkers (52) (Equation 49).

$$[Co^{I}]^{-} + [Co^{III}]^{+} \longrightarrow 2[Co^{II}] \qquad (49)$$

In basic, aqueous solution the reaction of B_{12s} and hydroxocobalamin, $[Co^{III}]^+$, was later found to proceed by a one-electron transfer process (53-54).

The instability of B_{12s} in neutral or acidic solution (55) has hindered the study of a wider range of metal complexes with the cobalt(I) species.

It has been found that B_{12s} can be generated electrochemically at pH 2.5-3.2 in aqueous glycine buffer to yield solutions that are reasonably stable for 1-2 hours. The kinetics of reduction of a family of chromium(III) complexes, $(H_2O)_5CrX^{2+}$ with $X = F^-$, Cl^-, Br^-, N_3^-, NCS^-, OAc^-, SH^-, and OH^-, by B_{12s} has been examined. The reaction produces B_{12r} and Cr_{aq}^{2+} as shown in Equation (50).

$$[Co^{I}]^- + (H_2O)_5CrX^{2+} \longrightarrow [Co^{II}] + Cr_{aq}^{2+} + X^- \qquad (50)$$

The rate of reaction has been found to increase with increasing atomic number of the halogen, for the halochromium(III) complexes. The work which will be described has been published (56).

EXPERIMENTAL

Materials

B_{12s}

Solutions of vitamin B_{12a} (Sigma Chemicals Co.) were made up in 0.05 M sodium perchlorate and 0.05 M glycine to which sufficient perchloric acid had been added to adjust the pH to its desired value in the range 2.5-3.2. The B_{12} solutions, under argon, were reduced to B_{12s} at an applied potential of -1.5 V supplied by a Princeton Applied Research potentiostat. The electrochemical cell consisted of a mercury pool cathode, a platinum wire anode, and a saturated calomel electrode separated from the cell by a bridge containing 0.05 M sodium perchlorate.

Miscellaneous reagents

$[(H_2O)_5CrF](ClO_4)_2$ Aqueous solutions were prepared from reaction of $[(NH_3)_5CoF](ClO_4)_2$ with chromium(II) perchlorate, followed by separations with Bio-Rad Cellex P cation-exchange resin and elution with 0.1 M $HClO_4$ (57).

$[(H_2O)_5CrBr](ClO_4)_2$ Aqueous solutions were prepared by reacting 40 drops Br_2 in 50 mL H_2O (0.1 M Br_3^-) with 0.12 M chromium(II) perchlorate in 0.1 M $HClO_4$. Separation was achieved with Dowex 50W-X8 cation exchange resin and elution with 0.8 M $NaClO_4$ and 0.05 M $HClO_4$ (57).

$[(H_2O)_5CrN_3](ClO_4)_2$ Aqueous solutions were prepared from reaction of $[(NH_3)_5CoN_3](ClO_4)_2$ with chromium(II) perchlorate, followed

by separation with Dowex 50W-X8 and elution with 0.8 M $NaClO_4$ and 0.05 M $HClO_4$ (58).

$[(H_2O)_5CrCl](ClO_4)_2$ Aqueous solutions were prepared according to the published procedure (57) by reacting Cl^- with chromium(III) perchlorate, followed by separation on Dowex 50W-X8 and elution with 0.5 M $NaClO_4$ and 0.5 M $HClO_4$.

$[(H_2O)_5CrNCS](ClO_4)_2$ Aqueous solutions were prepared according to the published procedure (57) by reacting SCN^- with chromium(III) perchlorate, followed by separation on Dowex 50W-X8 and elution with 0.5 M $NaClO_4$ and $HClO_4$.

$[(H_2O)_5CrOAc](ClO_4)_2$ Aqueous solutions were prepared according to the method of Deutsch and Taube (59). Chromium(II) perchlorate was added to a solution of $[(NH_3)_5CoOAc](ClO_4)_2$, followed by separation on Sephadex C-25 resin and eluted with 0.18 M $LiClO_4$ and 0.02 M $HClO_4$.

$[(H_2O)_5CrSH](ClO_4)_2$ Aqueous solutions were prepared by reacting polysulfide with chromium(II) perchlorate according to the procedure of Ramasami and Sykes (60). Polysulfide solutions were prepared by dissolving 0.04 mole Na_2S and 0.04 mole sulfur in H_2O and diluting to 1 L. Separation was achieved on Dowex 50W-X8 and elution with 0.9 M $NaClO_4$ and 0.1 M $HClO_4$.

$[(NH_3)_5CoOAc](ClO_4)_2$ Aqueous solutions were prepared by reacting $[(NH_3)_5Co(OH_2)](ClO_4)_3$ with 7.4 M NH_3, followed by a three-fold excess of acetic anhydride (61).

$[(NH_3)_5CoF](ClO_4)_2$ and $[(NH_3)_5CoN_3](ClO_4)_2$ The perchlorate salts were obtained from the corresponding fluoride and azide by dissolution in room temperature water, with stirring, adding a large excess of concentrated $HClO_4$, and cooling in ice.

$Co(ClO_4)_2$ Aqueous solutions were prepared from chromium(III)-perchlorate in dilute acid, by reduction over amalgamated zinc under a nitrogen atmosphere.

Glycine Reagent grade (Fisher) glycine was used as purchased.

Methods

Analyses and characterization

B_{12s} and B_{12r} The cobalt(I) and cobalt(II) corrin complexes were identified (1) by their UV-visible spectra, shown in Figure II-1. In deoxygenated aqueous 0.05 M glycine solutions at pH 2.5-3.2, the wavelengths of maximum absorbance for B_{12s} are (λ/nm(ε/cm^{-1} M^{-1})): 460 (0.25 x 10^4) and 385 (3.08 x 10^4). For B_{12r}, the oxidation product of B_{12s}, the absorption maxima are (λ/nm(ε/cm^{-1} M^{-1})): 470 (1.10 x 10^4); 405 (0.65 x 10^4); and 315 (2.21 x 10^4).

$[(H_2O)_5CrX](ClO_4)_2$ The synthesized chromium(III) complexes had UV-visible spectra which matched the published values as shown in Table II-1.

Kinetics

Rate determinations for the reaction of B_{12s} with the chromium-(III) complexes were made spectrophotometrically by following the

Figure II-1. Absorption spectra for vitamin B_{12s} (circles) and vitamin B_{12r} (triangles)

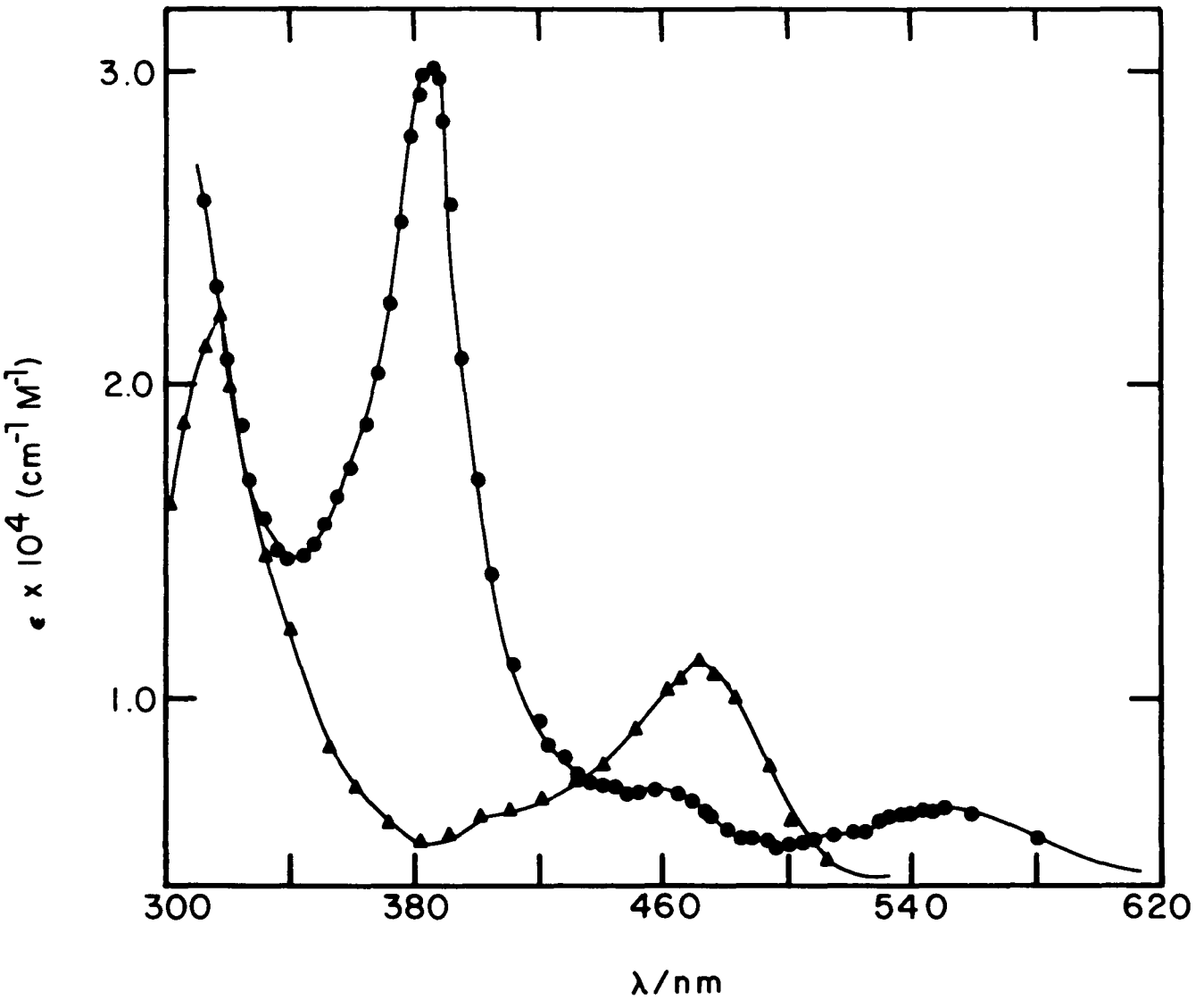

3.0
2.0
1.0
300
380
460
540
620
λ/nm
ε x 10⁴ (cm⁻¹ M⁻¹)

Table II-1. Visible spectra of $(H_2O)_5CrX^{2+}$ complexes in aqueous solution

X	Observed λ_{max}/nm		Literature λ_{max}/nm(ε/cm^{-1} M^{-1})		Reference
-OH	570	410	570 (13.3)	410 (15.8)	59
-F	585	415	595 (12.2)	417 (11.9)	57
-Cl	609	425	609 (16.4)	428 (20.8)	57
-Br	623	430	622 (19.9)	432 (22.4)	57
$-N_3$	585	433	585 (67.5)	434 (66.4)	58
-NCS	568	410	570 (31.5)	410 (33.6)	57
-OAc	570	410	570 (24.4)	410 (22.2)	59
-SH	575	433	575 (27.5)	435 (43.1)	60

decrease in $[B_{12s}]$ at 385 nm or the increase in $[B_{12r}]$ at 470 nm with use of a Cary 219 or a Durrum D-10 stopped-flow spectrophotometer. A PDP-15 computer interfaced to the Durrum instrument was used for data analysis. Solutions of $(H_2O)_5CrX^{2+}$ complexes were maintained in sufficient concentration to ensure pseudo-first-order conditions. Throughout the course of the reactions, the solutions were maintained at 25°C under rigorously oxygen-free conditions.

RESULTS AND DISCUSSION

Stoichiometry of Reaction

The 1:1 stoichiometry shown in Equation 50 was confirmed by spectrophotometric titration, and the quantitative formation of B_{12r} confirmed by the product spectra. The Cr^{2+} formed in the reaction of B_{12s} and $CrNCS^{2+}$ was detected by addition of $Co(NH_3)_5Cl^{2+}$ to convert Cr^{2+} to $CrCl^{2+}$. The resulting solution was first passed through a column of the macroreticular XAD-4 resin to remove all B_{12} species, and subsequently $CrCl^{2+}$ was separated from Co^{2+} by chromatography with 0.4 M $HClO_4$ on Dowex 50W-X8 cation exchange resin. The identity of $CrCl^{2+}$ was confirmed by its absorption spectrum and analyzed by chromate determinations. The yields of $CrCl^{2+}$ in two experiments are given in Table II-2.

Table II-2. Production of $(H_2O)_5CrCl^{2+}$

$[B_{12s}]_o$/ mmoles	$[CrNCS^{2+}]_o$/ mmoles	$[(NH_3)_5CoCl^{2+}]_o$/ mmoles	$[CrCl^{2+}]$/ mmoles	Yield
0.044	0.106	0.101	0.038	86%
0.070	0.113	0.101	0.048	68%

The findings in Table II-2 confirm the production of Cr^{2+} and, considering the practical difficulties and separations, especially the

problem of quantitative assay of the highly reactive and oxygen-sensitive B_{12s}, also constitute reasonable evidence for the quantitative occurrence of the reaction between B_{12s} and the $(H_2O)_5CrX^{2+}$ complexes.

Kinetics for the Reaction of B_{12s} with $(H_2O)_5CrX^{2+}$ Complexes

The reaction between B_{12s} and each of the CrX^{2+} species follows a second-order rate equation (Equation 51).

$$-d[B_{12s}]/dt = k_x[B_{12s}][CrX^{2+}] \quad (51)$$

The value of k_x was determined from the slope of the pseudo-first-order rate constant vs. $[CrX^{2+}]$ as shown in Figure II-2.

The kinetic effect of varying concentrations of glycine was measured, and the results are summarized in Table II-3. Rate constants were independent of glycine concentration in the range 0.02 - 0.15 M. Above 0.15 M glycine, the electrochemical reduction of B_{12a} becomes prohibitive owing to precipitation and turbidity in the solution. Table II-4 summarizes the reaction conditions and rate constants for all the complexes.

From the kinetic data, $Cr(H_2O)_6^{3+}$ is the only complex for which the rate of reaction with B_{12s} is pH dependent. The reaction occurs quite slowly, and the rate increases with decreasing $[H^+]$. It can be inferred from the pH dependence of the reaction rate that both $Cr(H_2O)_6^{3+}$ and $(H_2O)_5CrOH^{2+}$ react with B_{12s}. The proposed kinetic

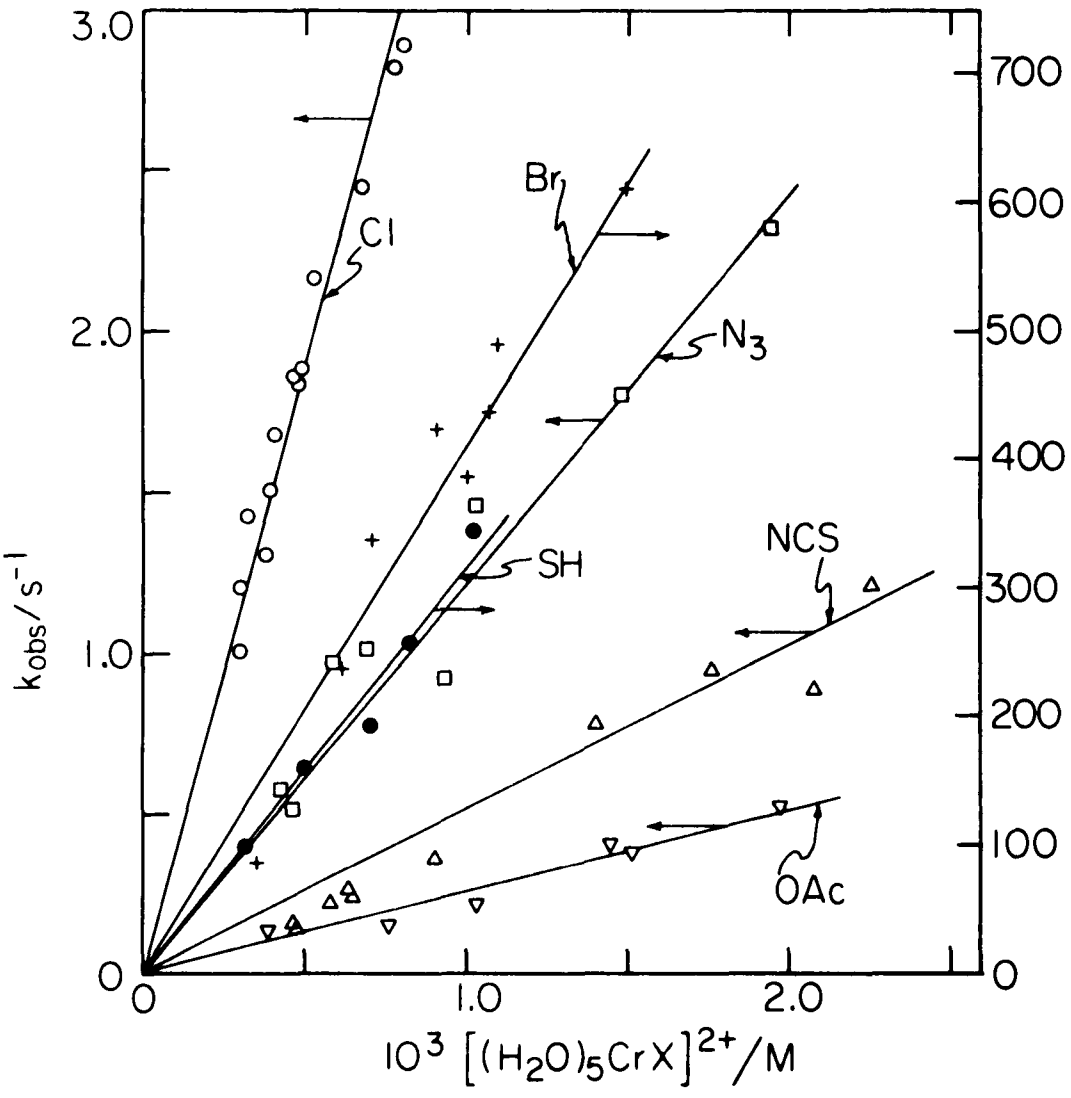


Figure II-2. Plot of k_{obs} vs. $[(H_2O)_5CrX]^{2+}$ for the reaction of vitamin B_{12s} with $(H_2O)_5CrX^{2+}$

Table II-3. Effect of variation of glycine concentration[a]

[Gly]/M	pH	$10^5[B_{12s}]$/M	$10^4[(H_2O)_5CrCl^{2+}]$/M	$10^{-3}k_{Cl}/M^{-1}s^{-1}$
0.02	2.8	3.29	3.78	3.38
0.02	2.8	3.29	4.74	3.93
0.05	3.2	3.15	3.89	3.84
0.05	3.2	3.15	4.78	3.84
0.05	3.2	3.24	6.78	3.61
0.15	3.2	2.51	3.01	3.98

[a]At 25°C in 0.05 M sodium perchlorate.

Table II-4. Kinetic data[a] for reactions of vitamin B_{12s} and $(H_2O)_5CrX^{2+}$ complexes

X	$10^5[B_{12s}]_o$/M	$10^3[CrX^{2+}]_o$/M	$k_x/M^{-1}\ s^{-1}$	K_x^b/M^{-1}	$k_xK_x/M^{-2}\ s^{-1}$
Cl[c]	1.9-3.2	2.90-8.12	$(3.80 \pm 0.30) \times 10^3$	1.1×10^{-1}	4.2×10^2
NCS	3.5	0.47-4.22	$(4.63 \pm 0.52) \times 10^2$	1.9×10^2	9.1×10^4
N_3	3.3-3.5	0.43-1.95	$(1.31 \pm 0.22) \times 10^3$	1.7×10^3[d]	2×10^6
OAc	3.5	0.39-1.98	$(2.49 \pm 0.50) \times 10^2$	---	---
F	10.0	1.12-2.27	$(8.1 \pm 1.0) \times 10^{-1}$	3.9×10^4	3.2×10^4
Br	3.1	0.36-1.51	$(4.00 \pm 0.75) \times 10^5$	2.3×10^{-3}	9.2×10^2
SH	3.5	0.31-1.02	$(3.08 \pm 0.21) \times 10^5$	---	---
OH[e]	3.0	4.5-8.8	7.3×10^{-1}	---	---
H_2O[e]	3.0	4.5-8.8	1.0×10^{-1}		

[a]At 25.0°C in 0.05 M sodium perchlorate and 0.05 M glycine (except as noted), pH 2.5-3.2.

[b]For the equilibrium $Cr^{3+} + X^- = CrX^{2+}$.

[c]Includes runs having 0.02 - 0.15 M glycine.

[d]The value given is that for VN_3^{2+} (assumed equal to K for CrN_3^{2+}) (62).

[e]Values determined from Equation 52 as described in the text.

scheme for the reactions of $Cr(H_2O)_6^{3+}$ and $(H_2O)_5CrOH^{2+}$ with B_{12s} is illustrated in Equations 52-54.

$$Cr(H_2O)_6^{3+} \underset{\leftarrow}{\overset{K_{Cr}}{\rightleftharpoons}} Cr(H_2O)_5OH^{2+} + H^+ \quad (52)$$

$$Cr(H_2O)_6^{3+} + B_{12s} \xrightarrow{k_{H_2O}} Cr^{2+} + B_{12r} \quad (53)$$

$$Cr(H_2O)_5OH^{2+} + B_{12s} \xrightarrow{k_{OH}} Cr^{2+} + B_{12r} \quad (54)$$

The formation of B_{12r} is given by the rate expression in Equation 55.

$$d[B_{12r}]/dt = (k_{H_2O}[Cr(H_2O)_6^{3+}] + k_{OH}[(H_2O)_5CrOH^{2+}])[B_{12s}] \quad (55)$$

The variation of k_2 ($= k_{obs}[Cr(III)]_{total}$) with $[H^+]$ is shown in Equation 56, where K_{Cr} is the acid ionization constant of $Cr(H_2O)_6^{3+}$, taken as 1.05×10^{-4} M (63).

$$k_2 = \frac{k_{H_2O} + k_{OH}K_{Cr}[H^+]^{-1}}{1 + K_{Cr}[H^+]^{-1}} \quad (56)$$

The kinetic data give a good fit to a plot of $k_2(1 + K_{Cr}[H^+]^{-1})$ *vs.* $[H^+]^{-1}$ (Figure II-3), yielding the values of k_{H_2O} and k_{OH} shown in Table II-4.

Decreasing from 3 to 1, the oxidation state of the cobalt atom in aquocobalamin, *i.e.*, passing from B_{12a} to B_{12r} and B_{12s}, results in various changes in axial ligations. The mechanism of the electrochemical reduction of B_{12r} into B_{12s} has been analyzed using mainly

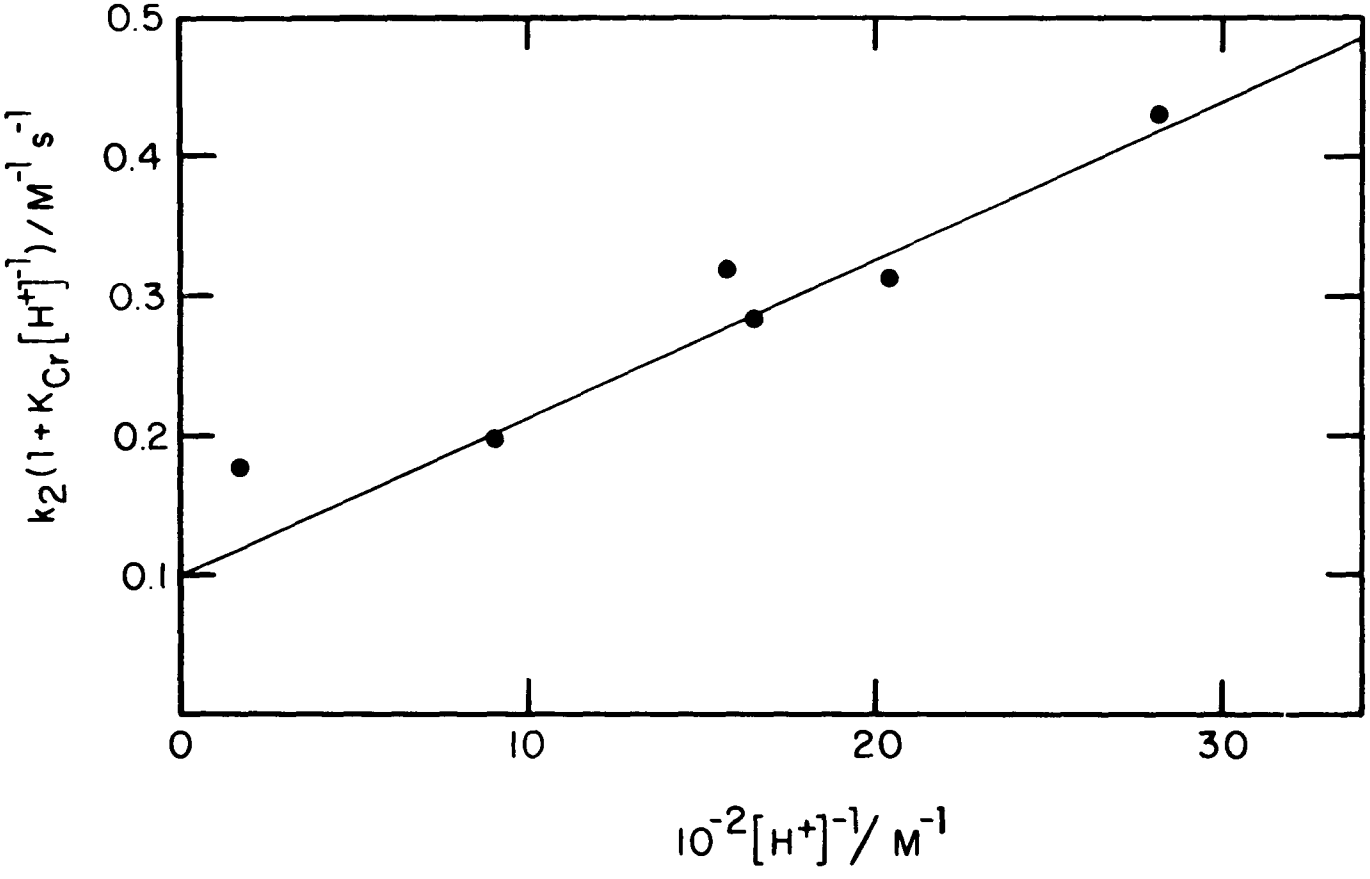


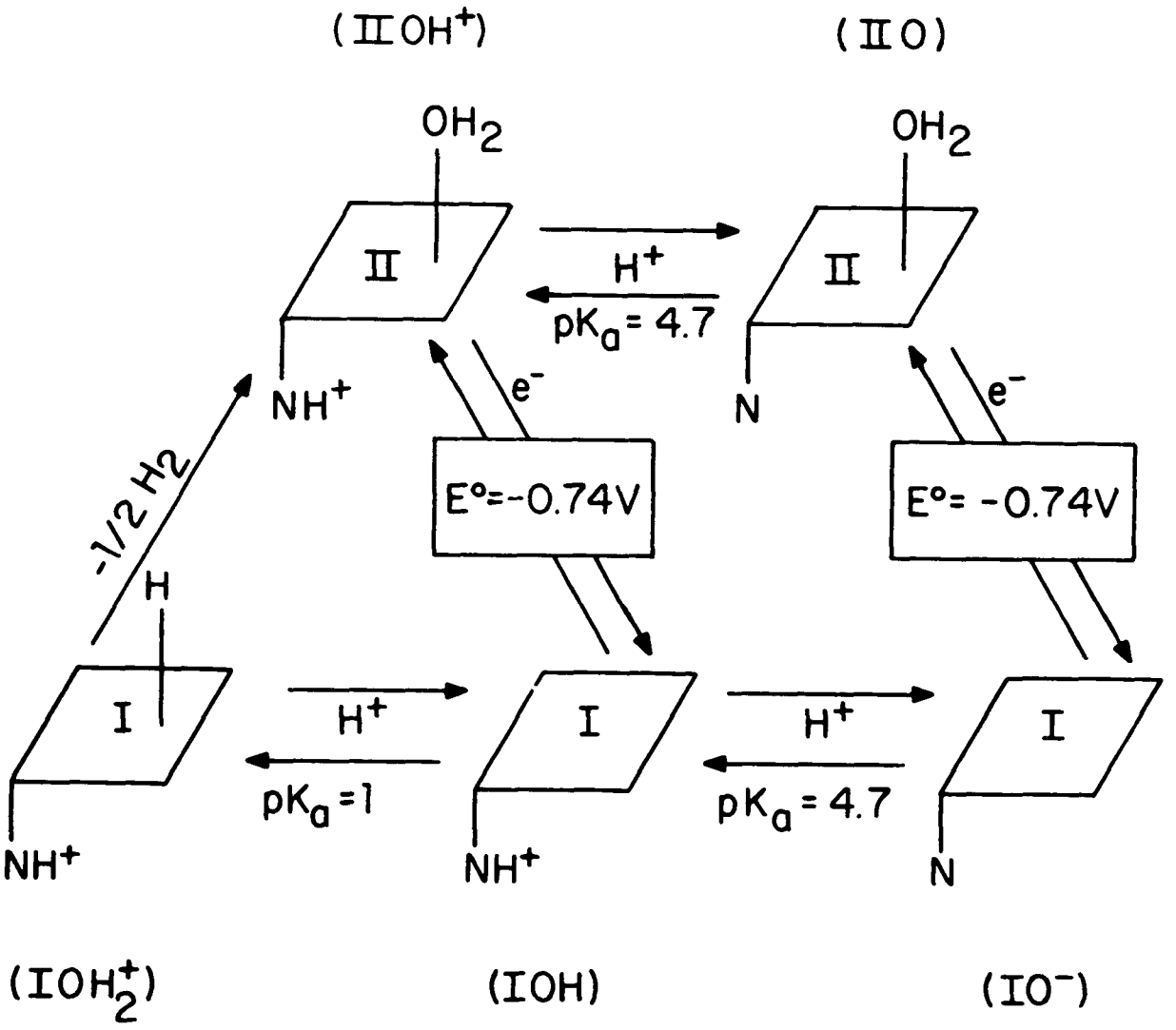
Figure II-3. Plot of $k_2 (1 + K_{Cr}[H^+]^{-1})$ vs. $[H^+]^{-1}$ with $K_{Cr} = 1.05 \times 10^{-4}$ M

cyclic voltammetry (43) with particular emphasis on the role of the cobalt coordination by the 5,6-dimethylbenzimidazole located at the end of the nucleotide side chain. The base-off forms of the B_{12r} - B_{12s} couple in acidic media are illustrated in Figure II-4. Within the pH range studied, 2.5 - 3.2, the predominant base-off forms of B_{12r} and B_{12s} present in solution are $IIOH^+$ and IOH. The original aquocobalamin, B_{12a}, exists as the base-on species from pH 0 to pH 8 (45). There is no kinetic influence on the reactions between CrX^{2+} complexes and B_{12s} from the protonation reactions of the 5,6-dimethylbenzimidazole nitrogen in the Co^I base-off species or of the cobalt atom in B_{12s}. This is apparent from the pH independence of the reaction rates.

Electron transfer between B_{12s} and the CrX^{2+} species through an inner-sphere activated complex, as depicted in Figure II-5, is a reasonable mechanism, based on the observation that the rates do change markedly with variation of group X. If electron transfer occurred through an outer-sphere mechanism, comparatively minor variation in the rates would be expected because X would be involved less directly in the activation process. Substitution at the Co(II) complex occurs far too rapidly to permit detection of the X-bound intermediate in Figure II-5.

For the halochromium(III) species studied, the rates of reaction vary according to F<Cl<Br. This reactivity order, in which the rate increases with increasing atomic number of the halogen, is known as "normal". The normal reactivity order (F<Cl<Br<I) is observed for the inner-sphere reductions of halogenopentaamminecobalt(III) complexes by

Figure II-4. Base-off forms of the B_{12r} - B_{12s} couple in acidic media


(IIOH+)
(IIO)
OH2
II
H+
pKa= 4.7
e-
NH+
N
-1/2 H2
E°=-0.74V
E°= -0.74V
H
I
H+
pKa=1
pKa= 4.7
NH+
N
(IOH2+)
(IOH)
(IO-)

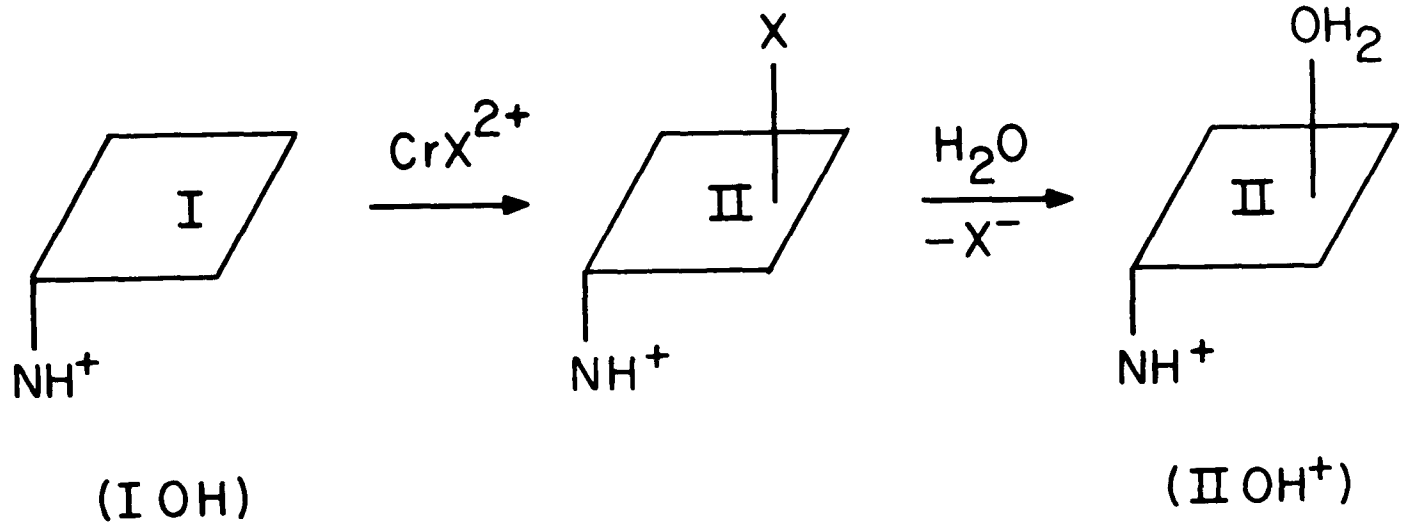


Figure II-5. Mechanism for electron transfer between vitamin B_{12s} and $(H_2O)_5CrX^{2+}$ species through an inner-sphere activated complex

chromium(II) (64) and pentacyanocobaltate(II) (65); for the outer-sphere reductions, by tris(bipyridyl)chromium(II) (66) and hexaammineruthenium-(II) (67). In contrast, the reductions by europium(II) (66) and iron(II) (68-69) which proceed by unknown mechanisms obey the inverse order (F>Cl>Br>I).

A comparison of the stabilities of the transition states, rather than the reactivity order for the series F, Cl, and Br could provide a useful indirect criterion for distinguishing between inner- and outer-sphere mechanisms. Following Haim's procedure (70-71), the "stability order" of the activated complexes is examined by computation of the equilibrium constant for the hypothetical process in which one potential bridging ligand X is replaced by another (Equation 57).

$$[(H_2O)_5CrXCo(corrin)]^{\ddagger} + Y^- = [(H_2O)_5CrYCo(corrin)]^{\ddagger} + X^- \quad (57)$$

The equilibrium constant for Equation 57 is related to the rate constants for the two individual reactions (k_x,k_y) and the stability constants for the chromium(III) complexes (K_x,K_y) by Equation 58.

$$K_{57} = \frac{k_x K_x}{k_y K_y} \quad (58)$$

A way to examine a series of reactions is to compare relative values of the product k_xK_x for each CrX^{2+} complex. These values are cited in Table II-4, showing the following trends in the "stability order"; (a) for halide-containing activated complexes, values of the quantity k_xK_x decrease in the order $F^- >> Cl^- \approx Br^-$; (b) for azide and

thiocyanate the order is N_3^- >> NCS^-. The stability order of the transition states and the products is the reverse of the stability order of the reactants which, according to Haim's classification (70-71), implies an inner-sphere reduction by a soft metal ion. The degree of hard- or soft-acid character of vitamin B_{12s} has not been established directly, but probably shows soft-acid character in view of its low-spin d^8 electronic structure.

CONCLUSIONS

All previous reactions involving vitamin B_{12s} have been done in basic solution where $[Co^{I}]^{-}$ exists in the base-on or unprotonated base-off forms. Under these conditions, the cobalt(I) corrin complex is mainly restricted to nucleophilic reactions. The possibilities of B_{12s} reacting as a one-electron reducing agent with other metal ions are greatly increased in acidic media, where the protonated base-off form predominates. Reasonably stable vitamin B_{12s} solutions can be electrochemically generated at pH 2.5 - 3.2 in aqueous glycine buffers.

The reduction of a family of chromium(III) complexes by $[Co^{I}]^{-}$ occurs by 1:1 stoichiometry of the reactants to produce B_{12r} and Cr_{aq}^{2+}. The formation of B_{12r} follows a second-order rate equation, first-order with respect to each reactant.

Electron transfer via an inner-sphere activated complex is a reasonable mechanism to invoke for this reaction, based on the large changes in the rates with variation of group X for the CrX^{2+} compounds. Were X involved less directly in the activation process, such as in outer-sphere electron transfer, comparatively minor variations might be expected. In addition, the "stability order" of the activated complexes is indicative of inner-sphere electron transfer.

GENERAL SUMMARY

The decomposition of α-phenylethyl(aquo)cobaloxime in acidic solution occurs by parallel homolytic and β-elimination pathways. In neutral solution and in the absence of a scavenger for $Co^{II}(dmgH)_2(OH_2)$, β-elimination is the only important decomposition process.

The reduction of substituted chromium(III) complexes by vitamin B_{12s} obeys a second-order rate law and occurs by an inner-sphere electron transfer reaction.

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