TMPP, 121-45-9; DMCA, 1467-79-4; THF, 109-99-9; $Cu(hfac)_2$, 14781-45-4.

**Supplementary Material Available.** The concentrations, volumes, and measured enthalpies for the $Cu(hfac)_2$-TMPP system in specified solvents will appear following these pages in the microfilm edition of this volume of the journal. Photocopies of the supplementary material from this paper only or microfiche (105 × 148 mm, 20× reduction, negatives) containing all of the supplementary material for the papers in this issue may be obtained from the Journals Department, American Chemical Society, 1155 16th St., N.W., Washington, D. C. 20036. Remit check or money order for \$3.00 for photocopy or \$2.00 for microfiche, referring to code number INORG-73-2809.

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Contribution from the School of Chemical Sciences and Materials Research Laboratory, University of Illinois, Urbana, Illinois 61801

# Comparative Study of Base Interactions with Three Methylatocobalt(III) Chelate Complexes[1]

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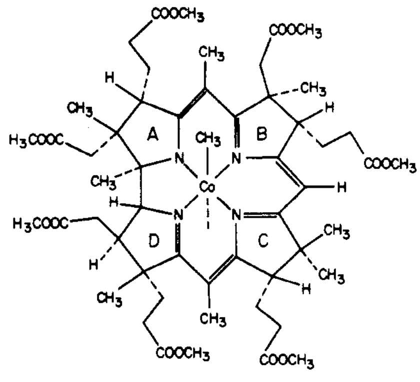
*Received March 30, 1973*

Proton magnetic resonance studies of ligand exchanges have been carried out for adducts of methylatobis(dimethylglyoximato)cobalt(III), $CH_3Co(dh)_2$, methylato-*N,N'*-ethylenebis(acetylacetoniminato)cobalt(III), $CH_3Co(bae)$, and methylato-[cobyrinic acid heptamethyl ester], I. Trimethyl phosphite, 1-(2-trifluoromethylphenyl)imidazole ($ImCF_3$), and 3-fluoropyridine were employed as bases. The rates of dissociation of $ImCF_3$ from the cobalt compounds are in the order $CH_3Co(bae) > I > CH_3Co(dh)_2$. The results reported here are the first quantitative data for base dissociation from $CH_3Co(bae)$ or from any alkylcobalt(III) corrinoid system.

The chemistry of cobalt(III) complexes containing an alkyl-cobalt bond and (in some instances) a base coordinated in the trans position is of interest because of the analogy with alkylcobinamides and cobalamins.[2-4] Complexes involving coordination by a planar, tetradentate ligand, such as bae = *N,N'*-ethylenebis(acetylacetoniminato),[5,6] salen = *N,N'*-ethylenebis(salicylideniminato),[7-9] saloph = *N,N'-o*-phenylenebis(salicylideniminato),[10,11] α-Me-salen = *N,N'*-ethylenebis(α-methylsalicylideniminato),[10,11] $(dh)_2$ = bis(dimethylglyoximato),[12,13] and 1-(diacetyl monoxime iminato)-3-(diacetyl monoximato iminato)propane,[14,15] (DO)(DOH)pn, have been studied.

The axially coordinated base has been shown to affect certain physical properties of the ligands in the cis position,[16] but the most interesting chemical effects result from its influence on the trans cobalt-ligand bond. Conversely, both the planar ligand system and trans ligand affect the tendency of the cobalt to bind a base in the sixth coordination position. Thus, for example, displacement of water from aquocobalamin[17] is several orders of magnitude more facile than the analogous reaction in aquocobaloxime complexes.[18]

We have been interested in the kinetics parameters for exchanges of ligands trans to the methyl groups in alkylcobalt chelate complexes.[19,20] The presence of an alkyl group clearly labilizes the sixth coordination position in both a kinetic and thermodynamic sense, but few data are available to assess the effect of the planar ligand on the kinetics of base exchange or the thermodynamics of the base-cobalt interaction. In this contribution we present comparative data for methylatobis(dimethylglyoximato)cobalt(III) adducts, $CH_3Co(dh)_2L$, adducts of methylato-*N,N'*-ethylenebis(acetylacetoniminato)cobalt(III), $CH_3Co(bae)L$ (Figure 1), and limited but highly significant data for methylato[cobyrinic acid heptamethyl ester], I.



I

## Results

Although data on the kinetics of axial base exchange are

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**Table I.** Kinetics Parameters for Dissociation of Methylcobalt Adducts

| Compd | L[d] | Temp, °C | Solvent | $k$, $sec^{-1}$ | $E_a$, kcal $mol^{-1}$ | $\Delta H^{\ddagger}$, kcal $mol^{-1}$ | $\Delta G^{\ddagger}$, kcal $mol^{-1}$ | $\Delta S^{\ddagger}$, cal $mol^{-1}$ $deg^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| $CH_3Co(dh)_2$ | TMP | 100 | $C_6H_5Br$[a] | 20.4 ± 3 | 22.9 ± 3 | 22.1 ± 3 | 19.8 ± 0.1 | 6.3 ± 3 |
| | | 100 | $C_6H_5NO_2$[a] | 11.9 ± 2 | 24.0 ± 3 | 23.3 ± 3 | 20.2 ± 0.1 | 8.4 ± 4 |
| | Fpy | 130 | $C_6H_5NO_2$ | 874 ± 400 | 23.0 ± 3[b] | 22.2 ± 3 | 18.4 ± 0.4 | 9.3 ± 8 |
| | $ImCF_3$ | 130 | $C_6H_5NO_2$ | 26.1 ± 5 | 27.9 ± 3 | 27.1 ± 3 | 21.2 ± 0.1 | 14.6 ± 7 |
| $CH_3Co(bae)$ | Fpy | −69 | $CH_2CH_2$ | 600[c] | | | 9.2 ± 0.9 | |
| | $ImCF_3$ | −86 | $CH_2Cl_2$ | 39.3 ± 5.8 | 9.0 ± 2 | 8.6 ± 2 | 9.4 ± 0.1 | 4.3 ± 3 |
| I | $ImCF_3$ | 49 | $CH_2Cl_2$ | 30.0 ± 10 | 19.3 ± 3 | 18.7 ± 3 | 16.7 ± 0.2 | 6.0 ± 3 |

[a] R. J. Guschl, R. S. Stewart, and T. L. Brown, *Inorg. Chem.*, in press. [b] Assumed activation energy. [c] Because the stopped-exchange region was not attained, the rate constant estimations are only rough. This value could conceivably be as large as 5000 $sec^{-1}$ or as low as about 250 $sec^{-1}$. [d] Abbreviations: TMP, $P(OCH_3)_3$; $ImCF_3$, 1-(2-trifluoromethylphenyl)imidazole; Fpy, 3-fluoropyridine.

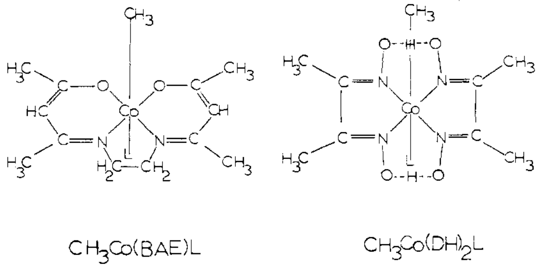

**Figure 1.** Structures of $CH_3Co(bae)$ and $CH_3Co(dh)_2$. L represents any coordinated Lewis base.

available for $CH_3Co(dh)_2L$ complexes,[19-21] there are none for $CH_3Co(bae)L$ or for any alkylcobalt(III) corrinoid system. It has been established that $CH_3Co(bae)$ is a much weaker acid than the $CH_3Co(dh)_2$. Thus, for example, the five-coordinate bae complex is easily prepared, and its crystal structure has been determined.[22] In this work the bases trimethyl phosphite (TMP), 1-(2-trifluoromethylphenyl)imidazole ($ImCF_3$), and 3-fluoropyridine (Fpy) form the basis for comparison between the cobalt systems. Using nmr techniques it is possible to observe exchange between free and coordinated base for all three bases with $CH_3Co(dh)_2$. Splitting of the axial methyl group resonance by scalar coupling with $^{31}P$ forms the basis of the observations with $P(OCH_3)_3$. The exchange between free and coordinated base is observed in $^{19}F$ spectra for Fpy and $ImCF_3$. With 3-fluoropyridine (Fpy) a $^{19}F$ chemical shift difference of 400 Hz between free and coordinated base was obtained for the $CH_3Co(dh)_2$ complex. With 1-(2-trifluoromethylphenyl)imidazole ($ImCF_3$), shift differences ranged from about 10 to 25 Hz over the temperature ranges of interest. In these compounds the presence of the fluorine-containing group should alter the basicity of the ligand only slightly as compared with the unsubstituted compound. In any case, our major interest is in comparing the interaction of a given base with different acid centers. To simplify the fitting procedures, $^1H$-$^{19}F$ decoupling was employed in obtaining all $^{19}F$ spectra.

The kinetics data based upon various computer-generated line shape fits are summarized in Table I. In all cases, the observed exchange rate is assumed to be governed by a first-order dissociation of base from the cobalt complex. For the $CH_3Co(dh)_2P(OCH_3)_3$ system, this was shown to be the case by examining the exchange in neat $P(OCH_3)_3$ as solvent. The value of the first-order rate constant at 100° under these conditions was 20.1 $sec^{-1}$, essentially the same as the value reported in Table I for $C_6H_5Br$ solution. In the $CH_3Co(bae)$-($ImCF_3$) system, a threefold change in the molar ratio of base to complex caused no apparent change in the exchange rates.

The results for $CH_3Co(dh)_2P(OCH_3)_3$-$P(OCH_3)_3$ exchange in bromobenzene are in excellent agreement with an earlier study.[20] Slow exchange of $P(OCH_3)_3$ with $CH_3Co(bae)$ was not observed even at −105° in $CH_2Cl_2$. The axial methyl group resonance remained a singlet throughout the temperature range studied. Although rate data were not obtainable, we were able to calculate equilibrium constants at temperatures below −18° by observing the change in chemical shift of the cobalt-bound methyl resonance at different base concentrations.[23] Values for the equilibrium

$$CH_3Co(bae) + P(OCH_3)_3 \overset{K_{eq}}{\rightleftharpoons} CH_3Co(bae)P(OCH_3)_3$$

in $CH_2Cl_2$ were obtained at various temperatures. A plot of $\ln K_{eq}$ *vs.* $1/T$ (Figure 2) yields a value of −4.7 ± 1 kcal $mol^{-1}$ for $\Delta H_{eq}$.

Attempts were made to observe exchange of coordinated $P(OCH_3)_3$ from I, by searching for evidence of splitting of the axial methyl group resonance due to scalar coupling with $^{31}P$. No evidence of a doublet was observed at the lowest temperature reached, −95°. This is not a definitive indication that exchange is rapid at this temperature, however, since the value of scalar coupling is not known; it could be zero or nearly so.

With both $CH_3Co(bae)$ and $CH_3Co(dh)_2$, $ImCF_3$ forms the kinetically most stable adducts among the ligands employed. The results for the $CH_3Co(bae)(ImCF_3)$-$ImCF_3$ exchange represent the first nmr observation of slow exchange for a $CH_3Co(bae)$ system. A set of observed spectra is shown in Figure 3. The Arrhenius plot for this system, Figure 4, yields an Arrhenius energy of 9.0 kcal $mol^{-1}$ with an uncertainty of 2 kcal $mol^{-1}$ at a 99% confidence level. With $ImCF_3$ as base it was possible also to observe $^{19}F$ resonances due to free and coordinated base with I. The kinetics parameters associated with the exchanges involving this base are given in Table I. Calculated and observed spectra are shown in Figure 5.

The 3-fluoropyridine exchange rates could not be accurately evaluated because of limitations occasioned by instrumental parameters, sample stabilities, and accessible temperature ranges. Nevertheless, the data given in Table I are of significance, because the difference in $\Delta G^{\ddagger}$ values for $CH_3Co(bae)$-(Fpy) and $CH_3Co(dh)_2$(Fpy) is much greater than the uncertainties in the individual values.

## Discussion

The data in Table I clearly demonstrate the comparatively weak acid character of $CH_3Co(bae)$. For trimethyl phosphite,

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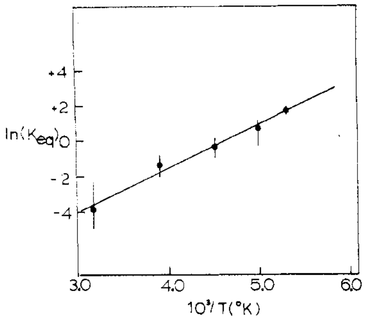

**Figure 2.** ln $K_{eq}$ *vs.* $1/T$, for the equilibrium $CH_3Co(bae) + P(OCH_3)_3 \rightleftharpoons CH_3Co(bae)P(OCH_3)_3$.

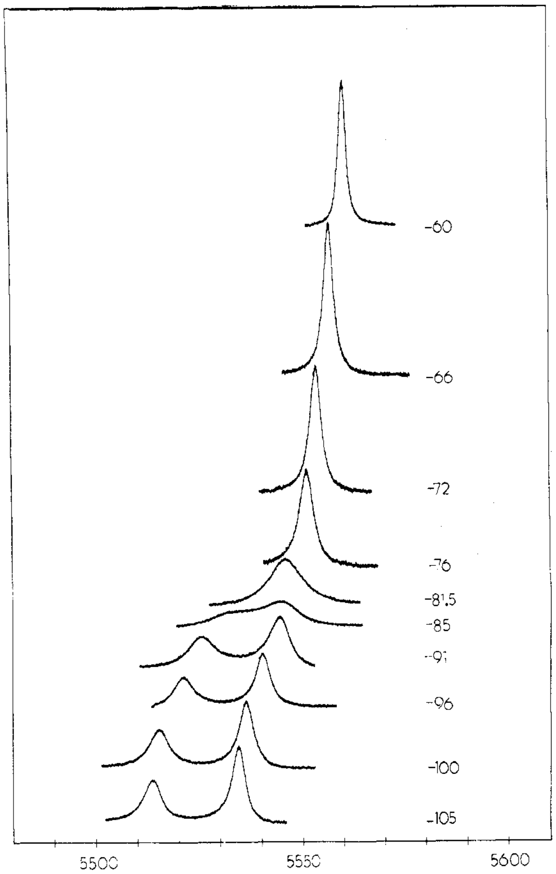

**Figure 3.** $^{19}F$ nmr spectra as a function of temperature for the $CH_3Co(bae)(ImCF_3)$ system in $CH_2Cl_2$. Shifts are shown in hertz upfield from $CFCl_3$. $^{19}F-^1H$ interactions have been decoupled.

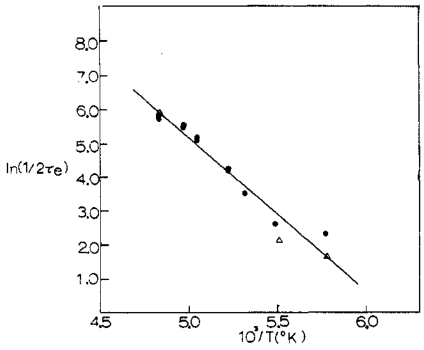

**Figure 4.** Temperature dependence of $k_1$ derived from computer fits of $^{19}F$ nmr spectra for the system $CH_3Co(bae)(ImCF_3)$ in $CH_2Cl_2$, as expressed in an Arrhenius plot. Values were taken from spectra run with different molar ratios of free base to coordinated complex: ●, 1.35:1; △, 3.65:1.

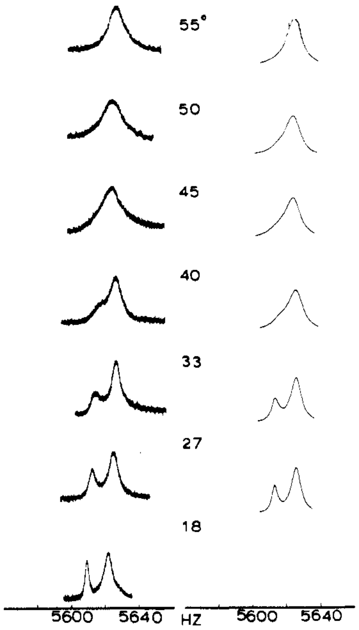

**Figure 5.** Calculated and observed $^{19}F$ nmr spectra at various temperatures for $ImCF_3$ + methylato[cobyrinic acid heptamethyl ester], I. The two resonances shown correspond to free and coordinated base.

which exhibits a coalescence temperature for exchange with $CH_3Co(dh)_2P(OCH_3)_3$ on the order of 100°, exchange with $CH_3Co(bae)P(OCH_3)_3$ was too rapid to be observed by nmr techniques at −100°. The weakness of the interaction is attested to by the small value of −4.7 kcal/mol obtained for $\Delta H$ from the temperature dependence of the equilibrium. Only for $ImCF_3$ was exchange sufficiently slow within the attainable temperature range to permit extensive studies.

Neither $CH_3Co(bae)$ nor $CH_3Co(dh)_2$ compounds exhibit any special proclivity for decomposition *via* rupture of the Co–C bond. It thus appears that the characteristics of the equatorial chelate ligand system which make for stabilization of the cobalt-carbon bond do not confine the acidity of the cobalt center toward axial base to a narrow range. At the same time, it has been widely recognized that the reactivity of the Co–C bond is dependent on the axial trans ligand.[24,25]

Costa has attempted quantitatively to order the alkylcobalt chelate complexes in terms of the electrochemical potentials for the reduction[26,27]

$$[RCo(chel)]^{n+} + e^- \rightarrow [RCo(chel)]^{(n-1)+}$$

(The axial base in these studies is presumably $H_2O$.) He obtains an order of increasing ease of reduction: bae < α-Me-salen < salen < saloph < cobalamin < $(dh)_2$ < (DO)(DOH)pn. This order should also be reflected in the kinetics of ligand exchange in the RCo(chel)L complexes if it accurately reflects the relative degree of electron donation of the equatorial chelate to the metal center. It has been argued that a strongly electron-donating ligand, *e.g.*, bae, would be expected more easily to form a pentacoordinate alkylcobalt complex[28] and obversely to exhibit faster axial ligand exchange than the more weakly donating chelate $(dh)_2$. The

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nmr exchange results (Table I) are consistent with this view; $\Delta G^{\ddagger}$ for base dissociation is from 9 to 12 kcal mol$^{-1}$ larger for $CH_3Co(dh)_2$ than for the analogous $CH_3Co(bae)$ complex.

On the other hand, the literature regarding axial base interactions with alkylcobinamides and -cobalamins presents something of a problem. It has been claimed,[2,28,29] largely on the basis of uv-visible spectral evidence, that methylcobinamide persists largely in the form of the five-coordinate species in water or methanol, even in the presence of bases such as $CH_3NC$, $P(C_6H_5)_3$, or $S(CH_3)_2$.[2] This suggests that the cobalt center is very weakly acidic. The formation constant in water for the six-coordinate benzimidazole species is reported[28] to be only about $10^2$.

The relative acidity of the cobalt center toward axial base in a $CH_3Co(chel)$ complex might be more unambiguously evaluated by studying the energetics or kinetics of base coordination in a relatively nonpolar, noninteracting solvent. Unfortunately neither methylcobalamin nor methylcobinamide possesses the requisite solubility properties. The heptamethyl ester of cobyrinic acid, I,[30] is ideal in this respect. The substitution of methyl ester for amido groups on the side chains and termination of the propyl side chain of the D ring in a methyl ester grouping can be expected to exert a minimum perturbation on the cobalt center, while at the same time conferring solubility in organic solvents on the compound. The overall charge on the cobalt-containing species is 1+, as in alkylcobinamides. Addition of $ImCF_3$ to methylene chloride, nitrobenzene, or chloroform solutions of I results in a color change from yellow to red. As noted earlier, attempts to observe a splitting in the axial methyl group resonance due to coupling with $^{31}P$ upon addition of $P(OCH_3)_3$ were unsuccessful, a result which parallels that obtained with $CH_3Co(bae)$. Coordination of $ImCF_3$ to I results, however, in a relatively less labile adduct than with $CH_3Co(bae)$, as evidenced by the kinetics parameters listed in Table I. Thus, in terms of the kinetics of base dissociation the alkylcobalt corrinoid system is intermediate between $CH_3Co(bae)$ and $CH_3Co(dh)_2$ in acid character.

These data are of special interest because they are free of the complexities associated with strong hydrogen bonding of solvent to side chains, leaving base, etc. Additional work to characterize more fully the acidity of the cobalt center in I would be of value, since the experimental results can be interpreted with less ambiguity than for equilibria involving alkylcobinamides in water or other highly polar medium.

Brodie and Poe reported[31] that the on-off exchange of benzimidazole in coenzyme $B_{12}$ in acidic aqueous solution is fast on the nmr time scale at room temperature and above, a result with which the present results are consistent. On the other hand, they reported[32] that water exchange from alkylaquocobinamides in DMSO is slow on the nmr time scale. This latter result we regard as probably incorrect. It is highly unlikely that water could compete effectively with DMSO in large excess for coordination. Also, the spectrum assigned to coordinated water is not consistent, in terms of the intensity distribution in the peaks, with the assignment made by Brodie and Poe.

The much-cited evidence that methylcobinamide is five-coordinate in water at room temperature has created an unwarranted impression of extremely weak acidity at the cobalt in this and related compounds. Oxygen donors invariably exhibit low formation constants toward coordination to cobalt in alkyl(chelate)cobalt complexes in solution. It is thus not surprising that water itself is not coordinated to cobalt in alkylcobinamides. At the same time, however, water is a strongly hydrogen-bonding solvent, capable of competing effectively with other acids for binding to a base such as $NH_3$, benzimidazole, etc. The fact that benzimidazole is apparently only rather weakly bound to methylcobalamin in water or methanol is undoubtedly due in large measure to solvent stabilization of base. The *kinetics* of base dissociation, on the other hand, should not be influenced so markedly by solvent, since the process is likely to be purely dissociative. Furthermore, dissociation of benzimidazole from cobalt in methylcobalamin or coenzyme $B_{12}$ may occur in biochemical situations in which water is not abundant in the immediate vicinity. It thus seems reasonable to suppose that the rate of dissociation of $ImCF_3$ from I represents a good estimate of the rate of dissociation of benzimidazole in methylcobalamin or coenzyme $B_{12}$. The rate of replacement of benzimidazole by another base would in most instances be smaller than this rate. Re-formation of the Co-N bond, which is competitive with new cobalt-base bond formation, is favored entropically by the fact that benzimidazole is constrained to remain in the vicinity of the cobalt by its attachment to the remainder of the molecule.

## Experimental Section

**Materials.** The methylatobis(dimethylglyoximato)cobalt(III) complexes (alkylcobaloximes) were prepared from the ligand-free dimer, which in turn was prepared by removal of water from methylaquocobaloxime by heating *in vacuo* at 80° for several hours. The methylaquocobaloxime was prepared by accepted procedures.[33] To prepare the adducts, the desired base was added to a suspension of dimer in benzene or other solvent used in the study. If the adduct was to be isolated, the solvent was removed and the adduct was either used directly or recrystallized. *Anal.* Calcd for $CoC_{12}H_{26}O_7N_4P$: C, 33.65; H, 6.12; N, 13.08. Found: C, 33.53; H, 6.14; N, 12.95. Calcd for $CoC_{19}H_{24}N_6O_4F_3$: C, 44.20; H, 4.65; N, 16.28. Found: C, 44.19; H, 4.84; N, 16.39. Calcd for $CoC_{14}H_{21}N_5O_4F$: C, 41.90; H, 5.27; N, 17.45. Found: C, 42.17; H, 5.14; N, 17.54.

Methylato-*N,N′*-ethylenebis(acetylacetoniminato)cobalt(III) ($CH_3Co(bae)$) was prepared following the procedure of Schrauzer.[34] The product isolated upon drying the solid in air did not contain axially bound water. The adducts of $CH_3Co(bae)$ were not isolated due to their low formation constants but were formed *in situ* in the nmr tube. *Anal.* Calcd for $CoC_{13}H_{21}N_2O_2$: C, 52.70; H, 7.14; N, 9.45. Found: C, 52.91; H, 7.04; N, 9.70.

All solvents were distilled and stored over freshly activated 4A molecular sieves prior to use. Trimethyl phosphite was freshly distilled (boiling range 111-112°). 3-Fluoropyridine was generously donated by the Chemicals Division of the Olin Corp., Stamford, Conn. 06904, and was used without further purification. 1-(2-Trifluoromethylphenyl)imidazole was prepared following a published procedure.[35] *Anal.* Calcd for $C_{10}H_7F_3N_2$: C, 56.60; H, 3.33; N, 13.21. Found: C, 56.52; H, 3.58; N, 13.38.

Vitamin $B_{12}$ was purchased from Sigma Chemical Co., St. Louis, Mo. The purple dicyanoheptamethyl ester (A) was prepared from cyanocobalamin following established preparative and purification procedures.[30] The alkylation procedure is a modification of that previously employed.

Dried A (0.134 g, 0.124 mmol) was dissolved into 15 ml of $CH_2Cl_2$. In a 250-ml separatory funnel, this solution was treated with 12 ml of a 30% $HClO_4$ solution for 2 min. The orange methylene chloride phase was separated from the upper acid phase and

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washed twice with 20 ml of distilled water. Finally this layer was taken to dryness by passing a stream of argon over it.

The resulting substance was redissolved into 30 ml of methanol and put into a 1-l. separatory funnel into which was added a solution made up of 150 ml of diethyl ether and 150 ml of dried hexanes. After shaking, 30 ml of $H_2O$ was added and the mixture was treated with 1.0 g of $NaBH_4$ with vigorous shaking and frequent venting. All of the following steps were carried out under subdued light.

The lower red-violet layer was removed and about 0.4 ml of $CH_3I$ (3.4 mmol) was injected into the dark green ether–hexane phase, whereupon the solution immediately became brick red. It was then shaken for 30 sec under an argon atmosphere and extracted with three 30-ml portions of a 1:1 water–methanol solution. This process completely decolorized the organic layer. The dark yellow methanol extracts were combined and stirred with 20 ml of a 15% $NaClO_4$ solution for 2 min. The resulting salt was then extracted from the methanolic solution with three treatments of 40 ml of $CH_2Cl_2$. The solvent was removed by nitrogen stream to afford the orange methylato[cobyrinic acid heptamethyl ester] perchlorate.

To prepare the corresponding trimethyl phosphite and imidazole adducts as tetraphenylborate salts, the perchlorate salt was dissolved into acetone and treated with equimolar quantities of both desired base and $NaB(C_6H_5)_4$. Water was then added until clouding to give a red methyl adduct with 1-(2-trifluoromethylphenyl)imidazole. However, the yellow-brown trimethyl phosphite adduct was isolated only as an orange oil. The adducts were dissolved into $CH_2Cl_2$ for nmr studies. The 100-MHz proton nmr of both adducts are shown in Figure 6; the axial methyl group absorptions appear at $\tau$ 10.17 for the $P(OCH_3)_3$ adduct (B) and $\tau$ 10.04 for the $ImCF_3$ adduct (A). Assignments for the remaining resonances of the chelate ring were possible by comparison with an earlier spectrum[30] of the aquo complex of I in $CDCl_3$.

**Nmr Spectra.** $^1H$ and $^{19}F$ nmr spectra were recorded on a Varian A-56/60 or HA-100 spectrometer, both equipped with a Varian temperature controller. All $^{19}F$ spectra involving proton decoupling were recorded on the Varian HA-100 spectrometer. All samples were degassed by successive freeze–thaw cycles under vacuum. They were then sealed in nmr tubes under vacuum and stored at −78° until time of use. Temperature measurements were made using an iron–constantan thermocouple with frequent calibrations made with methanol and ethylene glycol standards. The accuracy of these measurements is estimated at ±2°.

The kinetic parameter extracted from the nmr data is the mean exchange time $\tau_e$. The nmr exchange spectra were analyzed using a computer program described earlier,[36] but with an added iterative fitting routine. Input parameters were optimized by a supplementary program which successively varies input parameters until the best values are found as judged by an evaluation of the fit in terms of root-mean-square deviations. Initial input parameters were obtained from nonexchange spectra when possible. Where these were not accessible, the supplementary program was systematically used to generate values. The uncertainties quoted in the kinetic results reflect this. For final fits, a Calcomp routine was used to provide a visual comparison of calculated and experimental spectra.

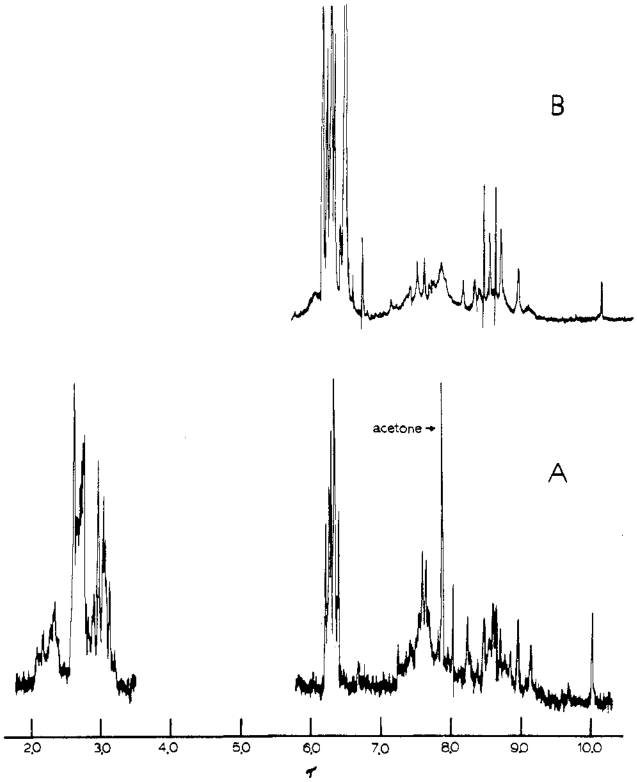

**Figure 6.** Proton nmr spectra at 100 MHz of $ImCF_3$ (A) and TMP (B) adducts of I.

**Acknowledgment.** We wish to thank J. D. Lipscomb for helpful discussions, T. A. Brethauer for aid in preparing ligands, and F. L. Slejko and R. S. Drago for the use of computer programs. We are grateful to Professor David Dolphin for assistance in obtaining information on the preparation of methylato[cobyrinic acid heptamethyl ester].

**Registry No.** $CH_3Co(dh)_2TMP$, 25586-92-9; $CH_3Co(dh)_2Fpy$, 42012-05-5; $CH_3Co(dh)_2ImCF_3$, 42012-06-6; $CH_3Co(bae)Fpy$, 42012-07-7; $CH_3Co(bae)ImCF_3$, 42012-08-8; $IImCF_3$, 42012-09-9; $CH_3Co(bae)P(OCH_3)_3$, 42012-10-2; ITMP, 42017-75-4; A, 36522-80-2.

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