2c, 139167-73-0; **2d**, 139167-74-1; **2e**, 139167-75-2; **3**, 123418-15-5; **4**, 1291-45-8; **5**, 51177-89-0; **7**, 76772-61-7; **8**, 92097-09-1; H_3C-$O_2CC{\equiv}CCO_2CH_3$, 762-42-5; zirconocene dichloride, 1291-32-3; (2-furyl)lithium, 2786-02-9; (2-thienyl)lithium, 2786-07-4; methyl(2-thienyl)zirconocene, 139167-76-3; dimethylzirconocene, 12636-72-5.

Supplementary Material Available: Details of the X-ray crystal structure analyses of **2d** and **2e**, including listings of atomic fractional coordinates, thermal parameters, and bond distances and angles (16 pages); listings of observed and calculated structure factors (46 pages). Ordering information is given on any current masthead page.

Alkali-Induced Decomposition of (2-Hydroxyethyl)aquocobaloxime: Resolution of a Long-Standing Mechanistic Dilemma

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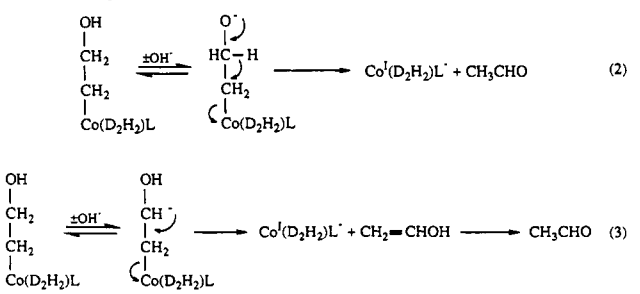
The kinetics of the alkali-induced decomposition of (2-hydroxyethyl)aquocobaloxime ($HOCH_2CH_2Co(D_2H_2)OH_2$) to form acetaldehyde have been studied in H_2O and in ^2H_2O, as well as the kinetics of the alkali-induced decomposition of $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ in H_2O. The results are consistent with a simple kinetic scheme in which both the aquo and hydroxo complexes are reactive, with the latter being about 20-fold more labile. The kinetics of the base-catalyzed exchange of the acetaldehyde methyl protons with solvent deuterons in phosphate-buffered ^2H_2O and those of the exchange of perdeuterioacetaldehyde methyl deuterons with solvent protons in phosphate-buffered H_2O were also measured. Under all conditions, these exchange processes were faster than the alkali-induced decomposition of the relevant (2-hydroxyethyl)-cobaloxime at the same basicity. In order to distinguish between a proposed mechanism in which acetaldehyde enolate is formed by elimination from a cis enolate intermediate and a mechanism in which acetaldehyde is directly formed by a 1,2-hydride shift, it was necessary to determine the isotopic composition of the acetaldehyde methyl group prior to its base-catalyzed exchange with solvent, when $HOCH_2CH_2$-$Co(D_2H_2)OH_2$ was decomposed in ^2H_2O and when $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ was decomposed in H_2O. This was accomplished by sampling reaction mixtures at various times, quenching the reaction, and converting the acetaldehyde to its oxime for mass spectral analysis. The results show that at very short reaction times there is very little or no solvent hydrogen isotope in the acetaldehyde methyl group but that solvent hydrogen isotope accumulates in the acetaldehyde methyl group with increasing time due to base-catalyzed exchange. Since enol acetaldehyde ketonization in aqueous base occurs by rapid protonation of the β-carbon of the enolate anion by solvent, these observations eliminate all mechanisms for the alkali-induced decomposition of (2-hydroxyethyl)cobaloximes in which enol acetaldehyde is the immediate product. It is therefore concluded that the reaction occurs by the 1,2-hydride shift mechanism.

Introduction

The alkali-induced decomposition of (2-hydroxyethyl)-cobaloximes,[1] to yield acetaldehyde and cob(I)aloxime (eq 1) was originally described by Schrauzer and Windgassen[2] over 20 years ago. In that work and in later publications,[3,4]

$$HOCH_2CH_2Co(D_2H_2)L \xrightarrow{OH^-} Co^I(D_2H_2)L^- + CH_3CHO \quad (1)$$

Schrauzer and co-workers proposed a 1,2-hydride shift mechanism (eq 2) for this reaction. The alternative base-catalyzed β-elimination mechanism (eq 3) was ruled out on the basis of the observation that (2-alkoxyethyl)-(pyridine)cobaloximes were stable in aqueous base.[2-4] Subsequent observations by others,[5,6] however, showed that (2-alkoxyethyl)cobaloximes, $ROCH_2CH_2Co(D_2H_2)L$, are, indeed, unstable in aqueous base, albeit significantly less so than (2-hydroxyethyl)cobaloximes.[7] However, the alkali-induced decomposition of $ROCH_2CH_2Co(D_2H_2)L$ evidently occurs by a completely different mechanism. Thus, β-elimination products (i.e., alkyl vinyl ethers) are *not* obtained. Instead, the observed products are ethylene and the alcohol derived from the alkoxide group, ROH.[5,6] In a careful mechanistic study,[6] ethylene was found to be formed from a series of five $ROCH_2CH_2Co(D_2H_2)OH_2$'s via a mechanism in which hydroxide ion attack on an equatorial quaternary carbon leads to formation of an altered cob(III)aloxime product in which one of the Schiff base linkages has become hydrated.[9] No alkyl vinyl ethers could be detected during decomposition of any of the



(1) Abbreviations: $RCo(D_2H_2)L$ = (alkyl)(ligand)cobaloxime = (alkyl)(ligand)bis(dimethylglyoximato)cobalt(III).

(2) Schrauzer, G. N.; Windgassen, R. J. *J. Am. Chem. Soc.* **1967**, *89*, 143.

(3) Schrauzer, G. N.; Sibert, J. W. *J. Am. Chem. Soc.* **1970**, *92*, 1022.

(4) Schrauzer, G. N.; Weber, J. H.; Beckham, T. M. *J. Am. Chem. Soc.* **1970**, *92*, 7078.

(5) Mock, W. L.; Bieniarz, C. *Organometallics* **1984**, *3*, 1279.

(6) Brown, K. L.; Szeverenyi, Z. *Inorg. Chim. Acta* **1986**, *119*, 149.

(7) Strongly donating axial ligands, L, such as pyridine, decrease the alkali-induced reactivity of $ROCH_2CH_2Co(D_2H_2)OH_2$'s[5] as well as that of $HOCH_2CH_2Co(D_2H_2)OH_2$.[8]

(8) Mock, W. L.; Bieniarz, C. *Organometallics* **1985**, *4*, 1917.

(9) For $ROCH_2CH_2Co(D_2H_2)OH_2$'s with good alkoxide leaving groups (R = C_6H_5 or CF_3CH_2) ethylene formation was quantitative. For complexes with poorer leaving groups (R = CH_3, CH_3CH_2, $(CH_3)_2CH$) hydroxide ion attack leads to less than stoichiometric yields of ethylene due to formation of a base-stable (alkoxyethyl)cobaloxime analogue, in which one of the Schiff base linkages is hydrated (vide infra).

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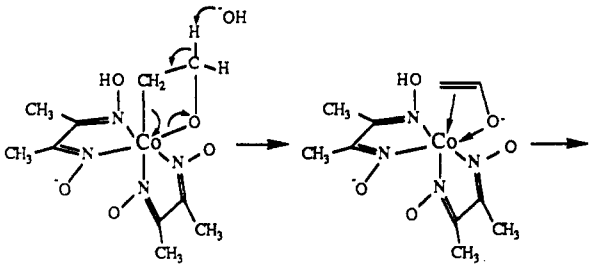
$ROCH_2CH_2Co(D_2H_2)OH_2$'s. This mode of decomposition, a carbon–cobalt bond cleavage induced by OH^- attack on the equatorial ligand to produce a cobalt(III) complex with the electrons from the Co–C bond leaving with the organic ligand, is a well-known mechanism common to simple $RCo(D_2H_2)L$'s such as $CH_3Co(D_2H_2)OH^-$.[10] In the case of the (hydroxyethyl)cobaloximes, evidently a much lower energy pathway is available for decomposition due to the presence of the β-hydroxyl group.

Despite the failure of (2-alkoxyethyl)cobaloximes to undergo β-elimination, the mechanism of acetaldehyde formation from (2-hydroxyethyl)cobaloxime remains controversial. Mock and Bieniarz[8] have proposed an internal, electrophilically assisted β-elimination from the *cis*-cobaloxime 1 (eq 4) derived from the equatorially and β-oxo-



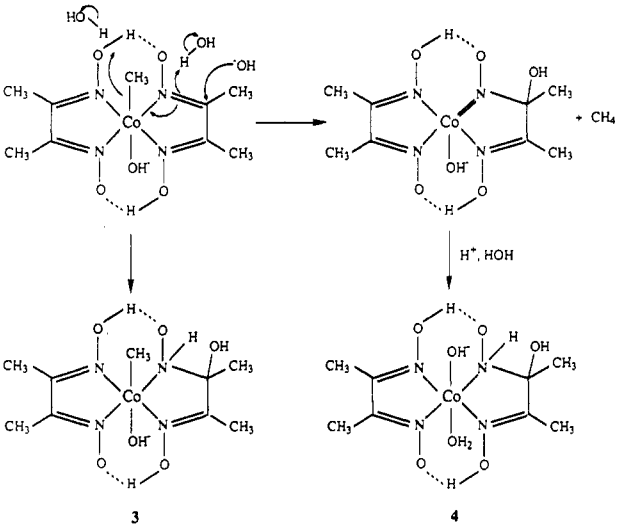
1 2

$$CH_2{=}CHO^- + Co^I(D_2H_2)OH_2 \qquad (4)$$

deprotonated pentacoordinate species. Formation of this intermediate was proposed to be the rate-determining step. Base-induced β-elimination of the organic ligand of 1 was then proposed to generate the Co^I π-complex **2**, from which the enolate of acetaldehyde dissociates. Support for the formation of the cis intermediate 1 was obtained from observation of base-induced, reversible formation of a species with magnetically inequivalent equatorial methyl groups from the base-stable analogue (3-hydroxypropyl)-cobaloxime. On the basis of the inequivalent methyl groups, this species was assigned a structure analogous to **1**.

While this mechanism (eq 4) is attractive in that it appears to explain both the stability of $ROCH_2CH_2Co(D_2H_2)L$ toward β-elimination (i.e., the cis intermediate analogous to 1 cannot be formed if the β-oxygen is alkylated) and the inhibition of $HOCH_2CH_2Co(D_2H_2)OH_2$ decomposition by axial ligands such as pyridine, it also poses several problems. First, base-induced formation of cobaloximes with magnetically inequivalent equatorial methyl groups is known to occur with (2-alkoxyethyl)cobaloximes.[6] For $ROCH_2CH_2Co(D_2H_2)OH_2$'s with relatively poor alkoxide leaving groups,[9] hydroxide ion attack on the equatorial ligand leads to partitioning between carbon–cobalt bond cleavage (to form ethylene, ROH, and a cobalt(III) cobaloxime analogue with one hydrated Schiff base linkage) and a base-stable (2-alkoxyethyl)cobaloxime analogue with a single hydrated Schiff base linkage. In fact, base-induced formation of such cobaloximes with magnetically inequivalent equatorial methyl groups does not require the presence of a heteroatom in the organic ligand, as demonstrated by the case of $CH_3Co(D_2H_2)OH_2$.[10] Here, hydroxide ion attack on the equatorial ligand (Scheme I) again leads to a partitioning in which either the carbon–cobalt bond is cleaved heterolytically (to form methane and, after neutralization, the equatorially altered cobaloxime **4**) or a base-stable (methyl)cobaloxime ana-

Scheme I



3 4

logue with a single hydrated Schiff base linkage (**3**) is formed. The latter reaction is reversible, as $CH_3Co(D_2H_2)OH_2$ is regenerated upon neutralization of **3**. In fact, reversible formation of cobaloxime analogues with hydrated Schiff base linkages does not even require the presence of an organic ligand, as aquocob(II)aloxime is known to undergo an identical, base-induced reaction,[11] Importantly, the base-induced decomposition of $CH_3Co(D_2H_2)OH_2$ to form methane is also inhibited by pyridine (as well as other axial ligands).[11]

The second problem with the mechanism of eq 4 is the reported base-induced formation of acetaldehyde from several (2-hydroxyethyl)cobalt complexes with macrocyclic equatorial ligands. These complexes include the boron difluoride bridged cobaloxime analogue,[3] the cobalt corrinoids cobalamin and cobinamide,[3] and cobalt aetioporphyrin I.[12] As it seems unlikely that these macrocyclic complexes can adopt the required cis geometry of the putative reactive intermediate 1 (eq 4), these complexes would have to react via a different mechanism. There are, however, examples of parallel organocobalt chemistry occurring by different mechanisms in cobaloximes (and other simple cobalt chelates) and in cobalt corrinoids.[13,14]

Finally, Mock and Bieniarz have reported a small (1.06 ± 0.023) but statistically significant primary deuterium isotope effect on the alkali-induced decomposition of [2-$^2H_1$](2-hydroxypropyl)cobaloxime.[8,16] This observation seems inconsistent with a mechanism (eq 4) in which formation of the cis-cobaloxime intermediate 1 is the rate-determining step. However, a primary deuterium isotope effect this small may well be appropriate for the hydride shift mechanism (eq 2) in which the rate-determining step involves perturbation of C–H bending modes only.

In order to resolve this dilemma it is necessary to determine the origin of the third proton of the methyl group of the product acetaldehyde formed in this reaction. If enol acetaldehyde is indeed the immediate product of

(10) Brown, K. L. *J. Am. Chem. Soc.* **1979**, *101*, 6600.

(11) Simandi, L. I.; Nemeth, S.; Budo-Zahonyi, E. *Inorg. Chim. Acta* **1980**, *45*, L143.

(12) Clarke, D. A.; Dolphin, D.; Grigg, R.; Johnson, A. W.; Pinnock, A. A. *J. Chem. Soc. C* **1968**, 881.

(13) Brown, K. L.; Salmon, L.; Kirby, J. A. *Organometallics*, in press.

(14) Alkyl iodides react with cob(II)alamin and with cobalt(II) model chelates to form (alkyl)cobalt complexes by dissimilar mechanisms.[15]

(15) Blaser, H.; Halpern, J. *J. Am. Chem. Soc.* **1980**, *102*, 1684.

(16) Inexplicably, Schrauzer and Sibert[3] reported a much larger isotope effect (5.5) for the same reaction.

base-induced $HOCH_2CH_2Co(D_2H_2)OH_2$ dealkylation, it will be rapidly ketonized under reaction conditions by a process known to occur via direct proton transfer from water to the β-carbon of the enolate anion.[17] Thus, if the final acetaldehyde methyl proton is derived from solvent, then the internal β-elimination mechanism (eq 4) is correct. In contrast, the hydride shift mechanism (eq 2) requires that the final acetaldehyde methyl proton come from the β-carbon of the organic ligand. Thus, in principle, the mechanisms may be distinguished by determination of the isotopic composition of the acetaldehyde methyl group from the decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in ^2H_2O. Unfortunately, the methyl protons of acetaldehyde are sufficiently acidic to undergo relatively rapid exchange with solvent deuterons in alkaline ^2H_2O. This exchange prevented Schrauzer and Sibert from determining the source of the final acetaldehyde methyl proton in their original work.[3] We now report the successful application of a method for time-resolved determination of the isotopic composition of the acetaldehyde methyl group in basic media by derivatization with hydroxylamine which resolves this mechanistic question. In order to apply this method, we have also studied the kinetics of the alkali-induced decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in water and in ^2H_2O[18] and of [1,2-$^2H_4$](2-hydroxyethyl)aquocobaloxime ($HOC^2H_2C^2H_2Co(D_2H_2)OH_2$) in H_2O, as well as the kinetics of the exchange of acetaldehyde methyl protons with solvent deuterons in ^2H_2O and the exchange of [1,2-$^2H_4$]-acetaldehyde methyl deuterons with solvent protons in H_2O. In addition to permitting a determination of the isotopic composition of the nascent acetaldehyde from the alkali-induced decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$, these data also allow a reinterpretation of the kinetic scheme for this decomposition previously reported by Mock and Bieniarz.[8]

Experimental Section

[1,2-$^2H_4$]Acetaldehyde (99 atom % ^2H) and [1,2-$^2H_4$]ethylene oxide (99 atom % ^2H) were from Cambridge Isotopes. Potassium deuteroxide, 40% in ^2H_2O (98+ atom % D) was from Aldrich. Acetaldehyde was redistilled immediately before use. All other reagents were obtained in the highest purity commercially available and used without further purification.

$HOCH_2CH_2Co(D_2H_2)OH_2$ was obtained by reaction of $Co^{II}(D_2H_2)OH_2$ (generated in situ) with ethylene oxide under hydrogen, essentially as described by Schrauzer and Windgassen,[2] except that pyridine was omitted from the reaction mixture. Due to the competition between alkylation of $Co^{I}(D_2H_2)OH_2^-$ and hydrogenation of the coordinated dimethylglyoxime under these conditions,[19] the yield of $HOCH_2CH_2Co(D_2H_2)OH_2$ was limited to about 50% (based on cobalt). ^1H NMR (C^2HCl_3): δ 1.60 (t, 2 H, J = 7.0 Hz, Co–CH_2), 2.26 (s, 12 H, CH_3), 2.87 (t, 2 H, J = 7.0 Hz, CH_2OH). Anal. Calcd for $C_{10}H_{21}N_4O_6Co$: C, 34.10; H, 6.01; N, 15.91; O, 27.25; Co, 16.73. Found: C, 34.02; H, 5.97; N, 16.01; O, 27.60 (by difference); Co, 16.40. $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ was synthesized analogously using [1,2-$^2H_4$]ethylene oxide. ^1H NMR (C^2HCl_3): δ 2.25 (s, 12 H, CH_3). ^2H NMR (CH_3OH/H_2O, 38% v/v): δ 1.31 (2^2H, Co–C^2H_2), 2.90 (2^2H, C^2H_2OH). Acetaldehyde oxime was prepared by the method described by Welcher.[20] The product was a mixture of the two geometrical isomers, as determined by ^1H NMR spectroscopy (^2H_2O): δ 1.81 and 1.79 (d's, 3 H, J = 5.7 and 6.0 Hz, CH_3), 6.92 and 7.47 (q's, 1 H, J = 5.5 and 6.0 Hz, CHO). MS: m/e 59 (49%, M^+), 44 (38%, $M^+ - CH_3$), 43 (11%, $M^+ - O$), 42 (23%, $M^+ - OH$), 41 (100%, $M^+ - H_2O$). [1,2-$^2H_4$]Acetaldehyde oxime was synthesized similarly, using [1,2-$^2H_4$]acetaldehyde. ^2H NMR (H_2O): δ 1.71 and 1.75 (3 ^2H, C^2H_3), 6.91 and 7.46 (1 ^2H, C^2HO). MS: m/e 63 (42%, M^+), 47 (9%, $M^+ - O$), 46 (15%, $M^+ - OH$), 45 (34%, $M^+ - O^2H$ and $M^+ - C^2H_3$), 44 (100%, $M^+ - OH^2H$).

UV–visible spectra were recorded on a Cary 14 or Cary 219 recording spectrophotometer. The alcohol dehydrogenase assay for acetaldehyde was carried out, after neutralization of samples, by the method of Racker.[22] Kinetic measurements were made on the latter instrument with its sample compartment thermostated to 25.0 ± 0.1 °C. Sample pH was maintained with 0.1 M phosphate buffers (pH 11.0–11.9) or with KOH (pH 12.0–14.0) for studies in water. For samples in ^2H_2O, p^{2}H was maintained with 0.1 M phosphate buffers (p^{2}H 11.2–12.7) or with KO^2H (p^{2}H 12.7–14.0). The observed rate constants were independent of phosphate buffer concentration at a given pH (or p^{2}H). Ionic strength was maintained at 1.0 M with KCl throughout. Observed first-order rate constants, k_{obs}, were obtained from the slopes of semilogarithmic plots of the increase in absorbance at 255 nm with time, for samples containing 2.5×10^{-5} to 5.0×10^{-5} M (2-hydroxyethyl)cobaloxime. Sample pH was measured after each kinetic run.

Values of the pK_a for the ionization of the axial water ligand of the (2-hydroxyethyl)cobaloximes (eq 5)[21,22] were determined by spectrophotometric titration at 25.0 ± 0.1 °C, ionic strength

$$HOCH_2CH_2Co(D_2H_2)OH_2 \overset{K_a}{\rightleftharpoons} HOCH_2CH_2Co(D_2H_2)OH^- + H^+ \quad (5)$$

1.0 M (KCl), at 465 nm ($HOCH_2CH_2Co(D_2H_2)OH_2$ in H_2O and ^2H_2O) or at 470 nm ($HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ in H_2O) using 2.0×10^{-3} M cobaloxime. Because of the alkali-induced decomposition, base end points for these titrations could not be determined directly. The acid end point was measured at pH 7.0, and absorbances of samples at pH (p^{2}H) 10.5–13.0 were monitored as a function of time and extrapolated to t = 0. Values of K_a (eq 5) were then obtained from the slopes of plots of eq 6, where A_{AH} is the acid end point absorbance, A_X is the absorbance at pH$_X$, and A_{A^-} is the base end point absorbance.

$$(A_{AH} - A_X) = -(A_{AH} - A_X)[H^+]/K_a + (A_{AH} - A_{A^-}) \quad (6)$$

pH measurements were made with a Radiometer PHM 64 or Radiometer PHM 84 pH meter equipped with a GK2402B combined electrode. Samples, standards (pH 7.00, 10.00, and 12.45 (saturated $Ca(OH)_2$)) and electrode were thermostated to 25.0 ± 0.1 °C. Values of p^{2}H for ^2H_2O solutions were calculated as p^{2}H = pH$_{obs}$ + 0.40. Deuteroxide ion concentrations were calculated from p^{2}H values and $K_W = 1.352 \times 10^{-15}$ for ^2H_2O.[23]

NMR measurements were made on a Nicolet NT 200 NMR spectrometer operating at 200.067 MHz (^1H) or at 30.711 MHz (^2H), a GE QE 300 NMR spectrometer operating at 300.669 MHz (^1H), or a Bruker AMX 300 NMR spectrometer operating at 46.072 MHz (^2H). For measurement of the rate of exchange of acetaldehyde methyl protons with solvent deuterons (or [1,2-$^2H_4$]acetaldehyde methyl deuterons with solvent protons) samples contained ca. 0.045 M acetaldehyde (or [1,2-$^2H_4$]acetaldehyde), ca. 0.025 M CH_3O^2H (or C^2H_3OH) as an integration standard, various concentrations of phosphate buffers, as appropriate, and KCl (ionic strength 1.0 M), and the probe temperature was maintained at 25 ± 1 °C. First-order rate constants for the exchange process were obtained from the slopes of semilogarithmic plots of the sum of the integrals of the acetaldehyde methyl group and the acetaldehyde hydrate methyl group relative to that of the integration standard.

GC/MS measurements were made on a Finnigan INCOS 500 GC/MS system with a Varian 3400 GC system and a 0.5-mm (o.d.) × 105-m DB624 GC column. Spectra were obtained in the electron

(17) Chiang, Y.; Hojatti, M.; Keefe, J. R.; Kresge, A. J.; Schepp, N. P.; Wirz, J. *J. Am. Chem. Soc.* **1987**, *109*, 4000.

(18) In ^2H_2O, the exchangeable hydrogens are immediately deuterated and the species decomposing is $^2HOCH_2CH_2Co(D_2^2H_2)O^2H_2$.

(19) (a) Simandi, L. L.; Szeverenyi, Z.; Budo-Zahonyi, E. *Inorg. Nucl. Chem. Lett.* **1975**, *11*, 773. (b) Simandi, L. L.; Budo-Zahonyi, E.; Szeverenyi, Z.; Nemeth, S. *J. Chem. Soc., Dalton Trans.* **1980**, 276.

(20) Welcher, F. J. *Organic Analytical Reagents*; Van Nostrand: New York, 1947; p 339.

(21) (a) Brown, K. L.; Lyles, D.; Pencovici, M.; Kallen, R. G. *J. Am. Chem. Soc.* **1975**, *97*, 7338. (b) Brown, K. L.; Awtrey, A. W. *Inorg. Chem.* **1978**, *17*, 111.

(22) Racker, E. *Methods Enzymol.* **1955**, *1*, 514.

(23) *Handbook of Chemistry and Physics*; Weast, R. C., Ed.; CRC Press: Cleveland, OH, 1975; p D131.

Table I. Rate and Equilibrium Constants for the Alkali-Induced Decomposition of (2-Hydroxyethyl)cobaloxime and [1,2-$^2H_4$](2-Hydroxyethyl)cobaloxime[a]

complex	solvent	pK_a[b]	$10^3k_2^{HOH}$,[c] M^{-1} s^{-1}	$10^2k_2^{OH^-}$,[c] M^{-1} s^{-1}	$k_2^{OH^-}/k_2^{HOH}$
$HOCH_2CH_2Co(D_2H_2)OH_2$	H_2O	12.19 ± 0.02	2.23 ± 0.24	3.81 ± 0.06	17.1 ± 2.1
$HOCH_2CH_2Co(D_2H_2)OH_2$[d]	^2H_2O	12.66 ± 0.03	5.99 ± 0.64	13.4 ± 0.4	22.4 ± 3.1
$HOC^2H_2C^2H_2Co(D_2H_2)OH_2$	H_2O	12.00 ± 0.05	1.51 ± 0.20	2.57 ± 0.05	17.0 ± 2.6

[a] 25.0 ± 0.1 °C, ionic strength 1.0 M (KCl). [b] Equation 5. [c] Scheme II and eq 7. [d] Reference 18.

impact mode using 70-eV ionization potential. The GC carrier flow rate was 10 mL/min and the column was temperature programmed as follows: 40 °C for 7 min, increase 1 °C/min to 50 °C and then 4 °C/min to 70 °C.

The experiment to determine the time dependence of the isotopic composition of acetaldehyde formed from the alkali-induced decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in ^2H_2O was performed as follows. A 0.144-g portion (0.408 mmol) of $HOCH_2CH_2Co(D_2H_2)OH_2$ was dissolved in 2.5 mL of CH_3O^2H, and the solution was added to 22.5 mL of ^2H_2O containing 0.1 M phosphate buffer, p^{2}H 12.56, and KCl (ionic strength 1.0 M), which had been preincubated at 25.0 ± 0.1 °C in a water bath. The sample was returned to the water bath, and after 30 s, and at various times thereafter, a 2.5-mL sample of the reaction mixture was removed and added to 1.1385 g of hydroxylamine hydrochloride (to which 0.5 mL of 50% NaOH had been added) to quench the reaction (final pH 5.66). The pH was adjusted to 7.0 with 50% NaOH, and oxime formation was permitted to occur for 30 min at room temperature. The oxime was extracted with six 3.5-mL portions of diethyl ether, and the combined extracts were evaporated to 0.5 mL under a stream of argon. In order to remove the residual exchangeable deuterium from the oxime hydroxyl, the concentrated extract was washed once with 0.5 mL of H_2O. Oxime was recovered from the H_2O wash by extraction with six 0.5-mL portions of ether. These extracts were combined with the original concentrated extract and concentrated again to 0.5 mL. The wash/back-extraction cycle was repeated once to ensure that residual exchangeable deuterium in the oxime was <1%. The extract was then concentrated to 0.1 mL. For GC/MS analysis, the solvent was transferred to *tert*-butyl methyl ether to avoid interference from the *m/e* 59 peak from diethyl ether. The concentrated ether extract was diluted with 1.0 mL of *tert*-butyl methyl ether and then reconcentrated to 0.10 mL. This was repeated once to reduce the diethyl ether content to <1%. The converse experiment, in which $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ was decomposed in H_2O was carried out analogously at pH 13 (0.12 M KOH), except that 0.072 g (0.204 mmol) of cobaloxime was used and water washing of the ether extract was omitted.

Results

Kinetics and Stoichiometry of (2-Hydroxyethyl)cobaloxime Decomposition. As is the case with other $RCo(D_2H_2)OH_2$,[21,24] $HOCH_2CH_2Co(D_2H_2)OH_2$ (and its deuterated analogue) undergoes reversible, visible spectral changes in aqueous base, indicative of formation of the hydroxo species, $HOCH_2CH_2Co(D_2H_2)OH^-$. As is the case for other $RCo(D_2H_2)OH_2$, these spectral changes are quite distinct from the UV spectral changes which accompany the ionization of the equatorial ligand of alkylcobaloximes and occur at much higher pH's. For these compounds, measurement of pK_a (eq 5) is complicated by the alkali-induced decomposition which prevents observation of the fully deprotonated species. However, satisfactory determination of these pK_a values (Table I) could readily be made using the spectrophotometric method described in the Experimental Section. The observed value of this pK_a for $HOCH_2CH_2Co(D_2H_2)$ in H_2O (12.19) is identical to that previously reported[21b] for $CH_3OCH_2CH_2Co(D_2H_2)OH_2$ and is quite similar to the previously reported value (12.02) for $C_6H_5CH_2CH_2Co(D_2H_2)OH_2$.[22] These data show that there is a significant solvent deuterium isotope effect on the ionization of coordinated water in $HOCH_2CH_2Co(D_2H_2)OH_2$ with $K_a(H_2O)/K_a(^2H_2O)$ = 2.95 ± 0.48. A similar value (3.98 ± 0.41) was previously observed (at 50 °C) for the K_a of $CH_3CH_2Co(D_2H_2)OH_2$ (pK_a = 13.12 in H_2O, 13.72 in ^2H_2O).[25] This is the expected solvent deuterium isotope effect, as the ionization of weak acids is known to be some 2.7–5.0-fold weaker in ^2H_2O than in H_2O.[26] However, there is an unexpected, inverse secondary deuterium isotope effect on K_a, with the ratio of K_a for $HOCH_2CH_2Co(D_2H_2)OH_2$ to that of $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ being 0.64 ± 0.10. This is in contrast to the effect of deuteration on simple organic acids which display small, normal secondary deuterium isotope effects with values ranging from 1.024 to 1.12 for compounds such as ^2HCOOH (1.12),[27] $C_6{}^2H_5NH_3^+$ (1.06),[28] $C_6{}^2H_5OH$ (1.12),[29] $C_6{}^2H_5COOH$ (1.024),[29] and C^2H_3COOH (1.06).[30]

The decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in aqueous base proceeded with first-order spectral changes at a given pH. The reaction was not catalyzed by phosphate buffer ions, as the observed first-order rate constant, k_{obs}, was independent of phosphate buffer concentration at a given pH over the range 0.05–0.50 M. The observed rate constants were also independent of the presence or absence of air in the reaction mixture. However, when $HOCH_2CH_2Co(D_2H_2)OH_2$ was decomposed anaerobically at pH 13.4 in the presence of 0.02 M pyridine, an intense purple spectrum was obtained with maxima at 540 and 443 nm and a long wavelength shoulder at 610 nm, confirming the formation of $Co^I(D_2H_2)py^-$.[2] This spectrum agreed with a published spectrum of $Co^I(D_2H_2)py^-$[4] and with a spectrum independently generated from $ClCo(D_2H_2)py$ by reduction with $NaBH_4$ catalyzed by a trace of $K_2[PdCl_4]$.[4] The latter allowed estimation of the molar absorbtivities ($\epsilon_{443} = 3.44 \times 10^3$ M^{-1} cm^{-1}, $\epsilon_{540} = 4.39 \times 10^3$ M^{-1} cm^{-1}, and $\epsilon_{610} = 3.94 \times 10^3$ M^{-1} cm^{-1}) from which the yield of $Co(D_2H_2)py^-$ from the decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in excess py was calculated to be 95.0 ± 4.7%. Decomposition of $CH_3OCH_2CH_2(D_2H_2)OH_2$ under identical conditions failed to produce the purple spectrum. Acetaldehyde was readily confirmed as the organic product by GC analysis. GC quantitation of the acetaldehyde from aerobic decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ at pH 12.8 showed the yield to be 91.6 ± 3.6%. In addition, the formation of acetaldehyde from aerobic reaction mixtures between pH 13.0 and 14.0 was quantitated by assay with alcohol dehydrogenase[22] (after neutralization of the samples) and gave a yield of 89.5 ± 5.9%. Kinetic analysis of the decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in the presence of various concentrations of pyridine confirmed the inhibitory effect of this ligand on the reaction, as previously described by Mock and Bieniarz.[8] At several pH's, analysis of the dependence of k_{obs} on the concentration of added pyridine led to estimates of the rate constant for decomposition of $HOCH_2CH_2Co(D_2H_2)py$

(24) Brown, K. L.; Awtrey, A. W.; LeGates, R. *J. Am. Chem. Soc.* **1978**, *100*, 823.
(25) Brown, K. L.; Hessley, R. K. *Inorg. Chem.* **1980**, *19*, 2410.
(26) Bunton, C. A.; Shiner, V. J. *J. Am. Chem. Soc.* **1961**, *83*, 42.
(27) Bell, R. P.; Miller, W. B. T. *Trans. Faraday Soc.* **1963**, *59*, 1147.
(28) Halevi, E. A. *Prog. Phys. Org. Chem.* **1963**, *1*, 109.
(29) Klein, H. S.; Streitwieser, A. *Chem. Ind.* **1961**, 180.
(30) Halevi, E. A.; Nussim, M.; Ron, A. *J. Chem. Soc.* **1963**, 866.

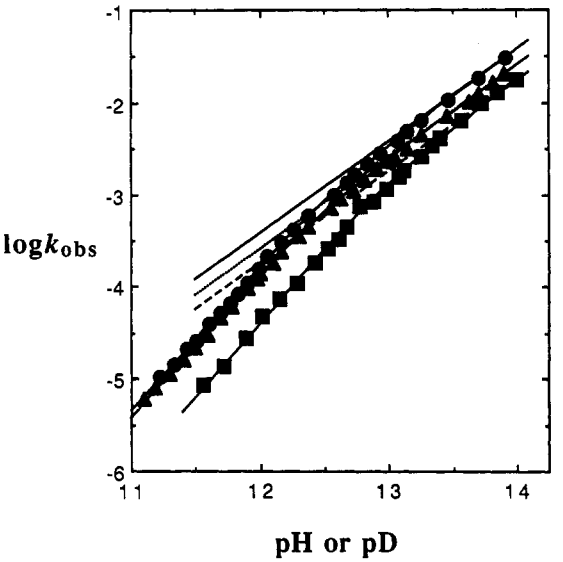


Figure 1. Plots of log k_{obs} vs pH or p^{2}H, for the base-induced decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in H_2O (●) or ^2H_2O (■) and $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ in H_2O (▲). The curved, solid lines were calculated from eq 7 and the rate and equilibrium constants given in Table I. The straight lines are first-order asymptotes (log $k_{obs} = k_2^{OH^-}[OH^-]$) calculated using the values of $k_2^{OH^-}$ in Table I for $HOCH_2CH_2Co(D_2H_2)OH_2$ in H_2O (solid line) or ^2H_2O (dashed line) and for $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ in H_2O (dotted line).

which were statistically indistinguishable from zero; i.e., the pyridine complex appears to be inert.

The pH dependence of the observed rate constants for $HOCH_2CH_2Co(D_2H_2)OH_2$ decomposition is shown in Figure 1. For most of the range of pH's at which measurements could be made, the dependence of k_{obs} on $[OH^-]$ is larger than first order. However, k_{obs} tends toward a first-order dependence at higher pH, as shown in Figure 1 by the first-order asymptote (solid, straight line). Although it is not immediately obvious from Figure 1, k_{obs} also tends toward a first-order asymptote at lower pH's (vide infra), although achievement of this first-order behavior cannot be demonstrated due to the slowness of the reaction at pH <11.0 ($t_{1/2}$ > 43 h). The pH-rate profile for $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ and the p^{2}H-rate profile for $HOCH_2CH_2Co(D_2H_2)OH_2$ in ^2H_2O[18] behave similarly (Figure 1).

The simplest explanation of this kinetic behavior is shown in Scheme II, which postulates that the two principal species present in solution, $HOCH_2CH_2Co(D_2H_2)OH_2$ and $HOCH_2CH_2Co(D_2H_2)OH^-$, decompose with second-order rate constants k_2^{HOH} and $k_2^{OH^-}$, respectively. A similar scheme was previously invoked to explain similar kinetic behavior in the base-induced β-elimination of $CH_3CH_2Co(D_2H_2)OH_2$ to form ethylene.[25] Application of the law of mass action leads to the rate law of eq 7. Since

$$k_{obs} = k_2^{HOH}[OH^-] + \{(k_2^{OH^-} - k_2^{HOH})K_a[OH^-]^2\}/(K_w + K_a[OH^-]) \quad (7)$$

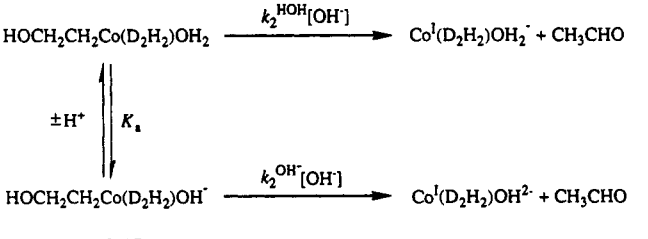
$$k_{obs}/[OH^-] = k_2^{HOH} + (k_2^{OH^-} - k_2^{HOH})\alpha_{cob} \quad (8)$$

$$\alpha_{cob} = \{[HOCH_2CH_2Co(D_2H_2)OH^-]\}/\{[HOCH_2CH_2Co(D_2H_2)OH_2] + [HOCH_2CH_2Co(D_2H_2)OH^-]\} \quad (9)$$

$$\alpha_{cob} = K_a/(K_a + [H^+]) \quad (10)$$

the values of K_a are independently known, k_2^{HOH} and $k_2^{OH^-}$ may be evaluted by use of eq 8, where α_{cob}, the fraction of (2-hydroxyethyl)cobaloxime present as the hydroxo species (eq 9), is readily calculated from eq 10. Plots of $k_{obs}/[OH^-]$ vs α_{cob} (eq 8) are shown in Figure 2, and the values of k_2^{HOH} and $k_2^{OH^-}$ derived from the intercepts and slopes of these plots are listed in Table I. The linearity of these plots attests to the adequacy of Scheme II. The values of $k_2^{OH^-}$ obtained from this treatment were used to calculate the first-order asymptotes in Figure 1.

Scheme II



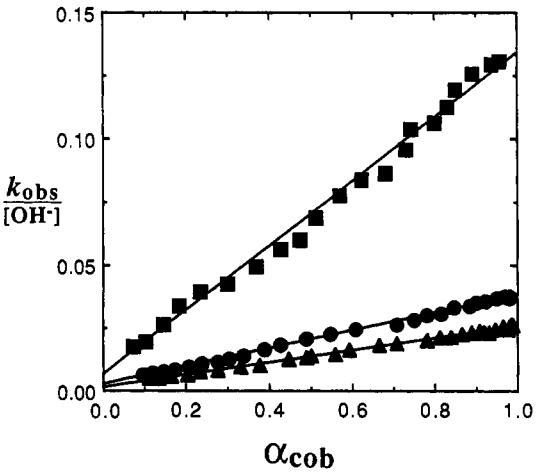


Figure 2. Plots of $k_{obs}/[OH^-]$ vs α_{cob}, the fraction of (2-hydroxyethyl)cobaloxime as the hydroxo complex (eq 9), according to eq 8: (●) $HOCH_2CH_2Co(D_2H_2)OH_2$ in H_2O; (■) $HOCH_2CH_2Co(D_2H_2)OH_2$ in ^2H_2O; (▲) $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ in H_2O. The solid lines are linear regressions from which the values of k_2^{HOH} and $k_2^{OH^-}$ in Table I were derived.

Perhaps the most surprising aspect of this analysis is that the reactivity of the hydroxo complex exceeds that of the aquo complex by about 20-fold (Table I). However, there is precedent for this in that the reactivity of the hydroxo complex of (ethyl)cobaloxime toward base-induced β-elimination to form ethylene also exceeds that of the aquo complex (albeit by about 2-fold at 50 °C).[25] In addition, in the base-induced decomposition of (methyl)cobaloxime, the hydroxo complex is the only active species. Neither the aquo complex nor any $CH_3Co(D_2H_2)L$ decomposes in aqueous base to form methane.[10]

The data in Table I also reveal substantial, inverse solvent deuterium isotope effects on the decomposition of the hydroxo species ($k_2^{OH^-}/k_2^{O^2H^-} = 0.28 \pm 0.01$) and the aquo complex ($k_2^{HOH}/k_2^{^2HO^2H} = 0.37 \pm 0.11$). These effects are very similar to the inverse solvent deuterium isotope effects previously determined for the β-elimination of (ethyl)cobaloxime (0.33 ± 0.02 for the hydroxo complex and 0.24 ± 0.02 for the aquo complex, at 50 °C).[25] There is also a significant effect of deuteration of the hydroxyethyl ligand on the decomposition rate constants, with the rate constant ratio for $HOCH_2CH_2Co(D_2H_2)OH_2$ to $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ being 1.48 ± 0.04 for the hydroxo complex and 1.48 ± 0.25 for the aquo complex. These ratios cannot, however, be directly interpreted as primary deuterium isotope effects, as the deuterated analogue contains deuterium atoms which are not translocated in the transition state and hence will cause a secondary isotope effect.

Table II. Rate and Equilibrium Constants for the Base-Catalyzed Exchange of Acetaldehyde Methyl Protons with Solvent Deuterons and the Exchange of [1,2-$^2H_4$]Acetaldehyde Methyl Deuterons with Solvent Protons[a]

	acetaldehyde in ^2H_2O	[1,2-$^2H_4$]acetaldehyde in H_2O
K_{hyd}[b]	1.32 ± 0.05	1.57 ± 0.04
10^2k_{exch},[c] M^{-1} s^{-1}		
OH^-	54.6 ± 3.3	3.74 ± 0.55
PO_4^{3-}	1.14 ± 0.26	0.139 ± 0.011
HPO_4^{2-}	0.0133 ± 0.0553	−0.003 15 ± 0.005 20
10^2k_{cat},[d] M^{-1} s^{-1}		
OH^-	127 ± 12	9.61 ± 1.66
PO_4^{3-}	2.64 ± 0.70	0.357 ± 0.037

[a] 25.0 ± 1.0 °C, ionic strength 1.0 M (KCl). [b] Equation 11. [c] Equation 12. [d] Equation 14.

Kinetics of Acetaldehyde Methyl Proton Exchange. In order to properly execute the oxime trapping experiment for the determination of the isotopic composition of the acetaldehyde formed by base-induced decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$, it was necessary to investigate the kinetics of exchange of the acetaldehyde methyl protons with solvent deuterons in ^2H_2O and the exchange of [1,2-$^2H_4$]acetaldehyde methyl deuterons with solvent protons in H_2O. Despite the fact that the hydration of acetaldehyde in water is relatively rapid,[31] the ^1H NMR spectrum of acetaldehyde in ^2H_2O clearly shows both the free aldehyde (2.28 ppm, d, 3 H, J = 2.8 Hz, and 9.66 ppm, q, 1 H, J = 2.9 Hz) and the hydrate (1.23 ppm, d, 3 H, J = 5.2 Hz, and 5.23 ppm, q, 1 H, J = 5.2 Hz). Similarly, the ^2H NMR spectrum of [1,2-$^2H_4$]acetaldehyde in H_2O also revealed both the aldehyde (2.16 ppm, 3 ^2H, and 9.66 ppm, 1 ^2H) and the hydrate (1.25 ppm, 3 ^2H, and 5.19 ppm, 1 ^2H),[32] indicating that the exchange between aldehyde and hydrate is stopped at both observation frequencies. Integration of these NMR spectra permitted evaluation of the hydration equilibrium constant, K_{hyd} (eq 11), the values of which are given in Table II. The value of K_{hyd} for acetaldehyde in ^2H_2O is in good agreement[34] with literature values determined both by UV[36] and ^{17}O NMR methods.[37,38]

$$K_{hyd} = [CH_3CH(OH)_2]/[CH_3CHO] \quad (11)$$

The rate of exchange of acetaldehyde methyl protons with solvent deuterons was studied in phosphate-buffered ^2H_2O between p^2H 11.1 and 11.8 (ionic strength 1.0 M, KCl) by measuring the sum of the integrals of the aldehyde and hydrate methyl ^1H resonances relative to that of an internal integration standard as a function of time. Under these alkaline conditions the equilibration of the aldehyde and hydrate is very rapid.[31] Similar measurements were made on [1,2-$^2H_4$]acetaldehyde in H_2O at pH's between 10.8 and 11.6 using ^2H NMR spectroscopy. Unlike the base-induced decomposition of (2-hydroxyethyl)cobaloxime, these exchange reactions proved to be buffer catalyzed; i.e., at a given pH the rate of exchange increased with buffer concentration and the rate law of eq 12 was applicable. In order to determine the individual rate

$$k_{exch}^{obs} = k_{exch}^{OH^-}[OH^-] + k_{exch}^{PO_4^{3-}}[PO_4^{3-}] + k_{exch}^{HPO_4^{2-}}[HPO_4^{2-}] \quad (12)$$

constants, the exchange rate constant at each pH was measured at five phosphate buffer concentrations between 0.03 and 0.30 M. Plots of k_{exch}^{obs} vs [buffer] (not shown) were linear, and the slopes and intercepts provided values of $(k_{exch}^{PO_4^{3-}}[PO_4^{3-}] + k_{exch}^{HPO_4^{2-}}[HPO_4^{2-}])/([PO_4^{3-}] + [HPO_4^{2-}])$ and $k_{exch}^{OH^-}[OH^-]$, respectively. From the latter, values of $k_{exch}^{OH^-}$ at several p^2H's were calculated and averaged to give the value listed in Table II. A plot (not shown) of the slopes of these correlations vs $\alpha_{PO_4^{3-}}$, the fraction of buffer species present as the conjugate base (eq 13), was also linear and permitted evaluation of $k_{exch}^{PO_4^{3-}}$

$$\alpha_{PO_4^{3-}} = [PO_4^{3-}]/([PO_4^{3-}] + [HPO_4^{2-}]) \quad (13)$$

and $k_{exch}^{HPO_4^{2-}}$ from its slope and intercept. The intercept of this plot was statistically indistinguishable from zero (i.e., $k_{exch}^{HPO_4^{2-}} = 0$). The rate data for the exchange of [1,2-$^2H_4$]acetaldehyde methyl deuterons with solvent protons behaved similarly and were treated in the same manner. The values of k_{exch} thus determined are listed in Table II. Since only the aldehyde methyl protons (pK_a = 16.73[17]), and not the hydrate methyl protons, are significantly acidic, true second-order rate constants k_{cat}, for the base-catalyzed exchange were calculated from the values of k_{exch} by correcting for the equilibrium concentration of free aldehyde, as in eq 14. These values are also listed in Table II.

$$k_{cat} = (1 + K_{hyd})k_{exch} \quad (14)$$

Inspection of the data in Table II shows that the deuteroxide ion is a better catalyst for acetaldehyde methyl proton exchange with solvent deuterium than the phosphate ion by 48-fold, while the hydroxide ion is a better catalyst than phosphate for [1,2-$^2H_4$]acetaldehyde methyl deuteron exchange with solvent protons by 27-fold. In both cases the Brønsted β value is roughly 0.35, suggesting that proton transfer from the acetaldehyde methyl group to the catalyst is somewhat limited in the transition state. From a combination of solvent and primary and secondary isotope effects, hydroxide ion-catalyzed deuterium exchange from [1,2-$^2H_4$]acetaldehyde is 13.2 times slower than deuteroxide ion-catalyzed exchange from acetaldehyde, and phosphate ion-catalyzed exchange is 7.4-fold slower.

Isotopic Composition of the Nascent Acetaldehyde. The difficulty in determining the isotopic composition of the acetaldehyde formed from the alkali-induced decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in ^2H_2O[18] can be appreciated from the data in Tables I and II. The rate constant for exchange of the acetaldehyde methyl protons with solvent deuterons exceeds that for $HOCH_2CH_2Co(D_2H_2)OH_2$ decomposition by 2-fold at p^2H 14.0, by 12.7-fold at p^2H 12.5 (in 0.1 M buffer), and by 28.8-fold at p^2H 11.1 (in 0.1 M buffer). The situation is somewhat less extreme for $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ decomposition in H_2O where the rate constant for exchange of [1,2-$^2H_4$]-acetaldehyde methyl deuterons with solvent protons exceeds that for $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ decomposition by 1.5-fold at pH 14.0, 1.8-fold at pH 12.5, or 17.8-fold at pH 11.1 (in 0.1 M buffer). Unfortunately, it is impossible to work at the highest alkalinities, where the relative rates of exchange and decomposition are the least unfavorable, due to the rapid rate of the exchange reaction under these

(31) Bell, R. P.; Rand, M. H.; Wynne-Jones, K. M. A. *Trans. Faraday Soc.* **1956**, *52*, 1093.
(32) As anticipated[33] due to the small magnetogyric ratio of the ^2H nucleus, the homonuclear ^2H–^2H couplings are not resolved.
(33) Mantsch, H. H.; Saito, H.; Smith, I. C. P. *Prog. NMR Spectrosc.* **1977**, *11*, 211.
(34) The solvent deuterium isotope effect on the hydration of aldehydes is known to be small ($K_{hyd}(H_2O)/K_{hyd}(^2H_2O) \sim 0.85$).[35]
(35) Gruen, L. C.; McTigue, P. T. *J. Chem. Soc.* **1963**, 5217.
(36) Bell, R. P.; Clunie, J. C. *Trans. Faraday Soc.* **1952**, *48*, 439.
(37) Fujiwara, Y.; Fujiwawa, S. *Bull. Chem. Soc. Jpn.* **1963**, *36*, 574.
(38) Evans, R. G.; Kreevoy, M. M.; Miller, G. R. *J. Phys. Chem.* **1965**, *69*, 4325.

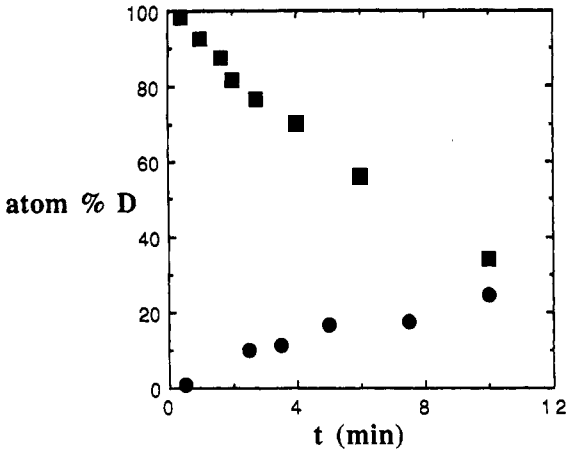


Figure 3. Time-dependence of the isotopic composition of the methyl group of acetaldehyde oxime derived from the acetaldehyde product of the decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in ^2H_2O, p^{2}H 12.56 (●), and that derived from the acetaldehyde product of the decomposition of $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ in H_2O, pH 13.0 (■).

conditions ($t_{1/2} \sim 18$ s for both acetaldehyde exchange in ^2H_2O at p^{2}H 14.0 and [1,2-$^2H_4$]acetaldehyde exchange in H_2O at pH 14.0). Since it is impossible to determine the isotope composition of the acetaldehyde methyl group in the absence of exchange with solvent, it is necessary to determine the isotopic composition of the acetaldehyde resulting from the base-induced decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in ^2H_2O as a function of time, in the time domain relevant to the exchange process. This proved possible, if challenging, by derivatization of the acetaldehyde in samples of decomposition reaction mixtures by reaction with hydroxylamine to form acetaldehyde oxime.

Complete decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ for 6 half-lives in ^2H_2O at p^{2}H 12.54 followed by conversion of the acetaldehyde product to its oxime gave [2-$^2H_3$]-acetaldehyde oxime (>97 atom % C^2H_3) as evidenced by its mass spectrum (m/e 62 (47%, M^+), 46 (5%, $M^+ - O$), 45 (27%, $M^+ - OH$), 44 (100%, $M^+ - C^2H_3$ and $M^+ - OH_2$)). Similarly, decomposition of $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ for 6 half-lives in H_2O at pH 13.0 resulted in [1-^{2}H]acetaldehyde oxime (m/e 60 (44%, M^+), 45 (24%, $M^+ - CH_3$), 44 (21%, $M^+ - O$), 43 (21%, $M^+ - OH$), 42 (33%, $M^+ - OH_2$ and $M^+ - O^2H$), 41 (100%, $M^+ - OH^2H$)). These results are as expected from the comparison of exchange and decomposition kinetics. However, when $HOCH_2CH_2Co(D_2H_2)OH_2$ was decomposed in ^2H_2O at p^{2}H 12.56 and samples were taken between 0.5 and 10 min after addition of the cobaloxime (corresponding to 0.73–13.7% decomposition at this p^{2}H), the results shown in Figure 3 were obtained after conversion of the acetaldehyde to oxime and mass spectral analysis. As seen in Figure 3, the oxime, and hence the acetaldehyde from which it was derived, contained less than 25 atom % deuterium in the oxime methyl group throughout this period and only 1.0% deuterium at the earliest time sampled. Similar results were obtained in the converse experiment in which $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ was decomposed in H_2O at pH 13.0 (Figure 3). In this experiment, samples taken between 0.4 and 10 min after addition of the cobaloxime corresponded to 5.6–75% decomposition, and contained between 98.4 and 34.0 atom % deuterium in the oxime methyl group. In experiments of this type, the kinetics of appearance of solvent hydrogen isotope in the acetaldehyde (and hence the oxime) methyl group are a sensitive function both of the acetaldehyde methyl exchange rate and of the rate of formation of acetaldehyde. Under the conditions chosen, the rate constants for exchange of the acetaldehyde methyl hydrogen isotope are quite similar for both experiments ($k_{exch}^{obs} = 3.74 \times 10^{-3}$ s^{-1} for $C^2H_3C^2HO$ at pH 13.0 and $k_{exch}^{obs} = 3.11 \times 10^{-3}$ s^{-1} for CH_3CHO at p^{2}H 12.56). However, the rate constant for formation of acetaldehyde in the experiment with $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ ($k_{obs} = 2.34 \times 10^{-3}$ s^{-1} at pH 13.0) is much larger than that for the $HOCH_2CH_2Co(D_2H_2)OH_2$ experiment ($k_{obs} = 2.45 \times 10^{-4}$ s^{-1} at p^{2}H 12.56). Thus, the more rapid rate of accumulation of solvent hydrogen isotope in the acetaldehyde methyl group in the former experiment is anticipated. In both experiments, the data clearly extrapolate to a composition in which the acetaldehyde does not contain any of the hydrogen isotope from the solvent. These results clearly establish that the nascent acetaldehyde formed from the alkali-induced decomposition of (hydroxyethyl)cobaloximes does not obtain the third proton of its methyl group from the solvent.

Discussion

Kinetics of (2-Hydroxyethyl)cobaloxime Decomposition. Mock and Bieniarz[8] previously studied the decomposition of (2-hydroxyalkyl)(pyridine)cobaloximes in aqueous base including (2-hydroxyethyl)-, (2-hydroxypropyl)-, *cis*- and *trans*-(2-hydroxycyclohexyl)-, and *trans*-(2-hydroxycyclopentyl)(pyridine)cobaloximes and proposed a kinetic scheme considerably more complicated than Scheme II. This more complicated kinetic scheme involves equatorial ionization of the pentacoordinate (2-hydroxyalkyl)cobaloxime, followed by rate-determining formation of the cis intermediate (1), requiring ionization of the axial 2-hydroxyethyl group. This scheme was based, in part, on kinetic measurements of the decomposition reactions in aqueous NaOH, ionic strength (1.0 M) maintained with NaCl. However, there are several reasons to question the validity of conclusions on the basis of these kinetic measurements. Values of pH were not measured either before or after kinetic determinations; the dependence of observed rate constants on hydroxide ion concentration was deduced from weight/volume and dilution considerations. These results were purported to show a second-order dependence on hydroxide ion concentration at low [OH^-], becoming first-order at intermediate [OH^-] and tending toward zero-order at very high [OH^-]. This was explained as being the consequence of the inhibitory effect of hydroxide ion due to formation of the inert $HOCH_2CH_2Co(D_2H_2)OH^-$ species, as well as the mandatory ionization of both the equatorial ligand and the organic ligand in order to achieve the transition state for the rate-determining step, i..e, the formation of the cis intermediate (1). While there is ample precedent for the equatorial ionization of (alkyl)(pyridine)cobaloximes[39] and (alkyl)aquocobaloximes (with sufficiently electron-withdrawing alkyl ligands[40]), the necessity for such ionization prior to formation of 1 is unexplainable. Furthermore, the tendency toward zero-order behavior at high [OH^-] was observed only for two of the three complexes for which observations could be made at sufficiently higher [OH^-], and for each of these two complexes only two data points at the highest [OH^-] deviate significantly from a linear, first-order dependence on [OH^-]. As both of these data points occur at [OH^-] > 1.0 M, the ionic strength in these

(39) Values for the pK_a for equatorial ionization of (alkyl)(pyridine)-cobaloximes vary from 11.77 to 13.93 for various alkyl ligands.[21]

(40) Equatorial ligand ionization (subsequent to axial water ligand ionization) has been observed for only one (alkyl)aquocobaloxime, (cyanomethyl)aquocobaloxime (pK_a = 14.16).[21]

experiments is not the same as that maintained for all of the other measurements. Since the ionizations involved in the decomposition mechanism as well as the activity coefficient of hydroxide ion must both be expected to be significantly ionic strength-dependent, mechanistic conclusions should not be drawn on the basis of these four data points.

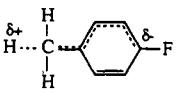
The use of the (2-hydroxyalkyl)(pyridine)cobaloximes represents an additional complication to the kinetic measurements of Mock and Bieniarz,[8] since the pyridine complexes have been shown, both by these authors and by us, to be inert. Using a value for the formation constant for (2-methoxyethyl)(pyridine)cobaloxime from the aquo complex and pyridine as a model, Mock and Bieniarz calculated that <8% of the (2-hydroxyethyl)cobaloxime would be present as the pyridine complex at their working concentration of 6.0×10^{-5} M complex. Since the equilibrium constants for formation of the (alkyl)(pyridine)-cobaloximes are significantly pH-dependent,[21] this means that the amount of inert pyridine complex will vary with basicity. However, since at most only 8% of the complex could presumably be present as the unreactive pyridine complex, this variability, while undesirable, does not seem sufficiently large to confound the question of reaction order. However, the formation constants for the pyridine derivatives of the other four (2-hydroxyalkyl)cobaloximes studied are unknown. Furthermore, the conclusion that insignificant amounts of the pyridine complexes persist under reaction conditions is contradicted by these author's own results. Thus, from the dependence of the decomposition of (2-hydroxyethyl)cobaloxime on the concentration of added pyridine, Mock and Bieniarz[8] report a value of 1.9×10^{-4} M^{-1} for the dissociation constant[41] for pyridine from $HOCH_2CH_2Co(D_2H_2)py$ in 0.5 M NaOH. Under these conditions, 20% of the complex exists as the unreactive pyridine complex and this value must vary significantly with basicity. Hence, the observed order of the decomposition reaction in hydroxide ion is complicated by the presence of significant but varying amounts of the inert pyridine complex throughout the range of alkalinity studied. Given these complications, it seems unwise to draw mechanistic conclusions from such kinetic data.

As can be seen in Figure 1, the observed rate constants for (2-hydroxyethyl)aquocobaloxime decomposition at relatively low basicity show an apparent order in hydroxide ion which is distinctly greater than 1, and, in fact, approximates a second-order dependence. A first-order dependence is achieved at high pH, but there is no discernable tendency for the order to decrease below 1 at pH's (or pD's) up to 14.0. As shown in Figure 2 and the associated eqs 7–10, this behavior is adequately explained by the simple kinetic sheme shown in Scheme I. In the absence of any compelling data to the contrary, there is no reason to assume a more complicated kinetic scheme is operative.

(41) The disclaimer[8] that the apparent "inhibition constants" for pyridine dissociation do not represent true dissociation constants for the (2-hydroxyalkyl)(pyridine)cobaloximes due to complications from the relatively slow rate of pyridine dissociation is incorrect. The rate law for achievement of the axial ligation equilibrium is $k_{on}[RCo(D_2H_2)OH_2][py] + k_{off}[RCo(D_2H_2)py]$, where k_{on} and k_{off} are the rate constants for pyridine association and dissociation, respectively. Hence, the rate of pyridine dissociation must always exceed $k_{off}[RCo(D_2H_2)py]$. For $CH_3OCH_2CH_2Co(D_2H_2)py$, k_{off} is 1.2×10^{-1} s^{-1} for the neutral species and is expected to be 2–3-fold higher for the anion, $CH_3OCH_2CH_2Co(D_2H)py^-$.[21] Hence, under all conditions, the axial ligation equilibrium is achieved with a half-life >5.8 s, i.e., far faster than the rate of complex decomposition. If it were correct that the rate of dissociation of pyridine from the (2-hydroxyalkyl)(pyridine)cobaloximes is comparable to the rate of decomposition of the aquo species, all of the kinetic observations using the pyridine complexes would be invalid.

Isotope Effects. The data in Table I demonstrate two interesting equilibrium isotope effects on the ionization of the axial water ligand of (2-hydroxyethyl)aquocobaloxime: the solvent deuterium isotope effect, which is normal ($K_a(H_2O)/K_a(^2H_2O) = 2.95 \pm 0.48$) and the secondary deuterium isotope effect of $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$, which is inverse ($K_a(H)/K_a(^2H) = 0.64 \pm 0.10$). The normal solvent deuterium isotope effect is anticipated and falls within the range 2.7–5.0 observed for the dissociation of acids in ^2H_2O.[26] These effects have been explained by comparison of the stretching frequencies and zero-point energies of the bonds to hydrogen in the acid and in the solvent molecules hydrogen-bonded to the acid, its conjugate base, and hydronium ion.[26] This treatment accounts for the observation that the magnitude of the normal solvent deuterium isotope effect on the ionization of an acid increases with decreasing acid strength.[42,43] This trend is also seen in the ionization of the axial water ligand of (alkyl)aquocobaloximes from a comparison of the isotope effect for $CH_3CH_2Co(D_2H_2)OH_2$ (3.98 ± 0.41, $pK_a(H_2) = 13.12$)[25] to that for $HOCH_2CH_2Co(D_2H_2)OH_2$ (2.95 ± 0.48, $pK_a(H_2O) = 12.19$, Table I).

The inverse secondary deuterium isotope effect on the ionization of the axial water ligand of $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ is more interesting, as it is opposite to, and of greater magnitude than, the normal secondary deuterium isotope effects on the ionization of organic acids (1.024–1.12).[27–30] While secondary deuterium isotope effects are due to the influence of isotopic substitution on vibrational frequencies, they are often conveniently viewed as being due to the "inductive", "steric", and/or "resonance" effects of deuterium relative to hydrogen.[28,44] Seen in this light, it is clear that deuterium acts as if it were more "inductively" donating than hydrogen, as shown by the secondary deuterium isotope effects on the ionization of organic acids,[27–30] the ionization of triphenylmethyl chloride in SO_2,[45] and the upfield shifts of ^1H and ^{19}F resonances in α-deuterated compounds.[28,46,47] However, there are numerous instances in which a C^2H_3 group appears to show less electron donation than a CH_3 group. Such β secondary deuterium isotope effects have long been thought to be due to hyperconjugation.[28,44,48–50] For instance, in fluorotoluenes there is a downfield shift of the ^{19}F resonance of the methyl-deuterated analogue in the para isomer, but not in the meta isomer.[51] This has been attributed to participation of the hyperconjugation resonance hybrid **5**. Due to the loss of zero-point energy in



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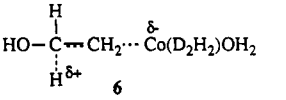
the hyperconjugated species, hyperconjugation is less significant for the deuterated analogue, resulting in the observed shift. There is now a substantial body of evidence that hyperconjugation is the principal source of β secondary deuterium isotope effects in organic systems in-

(42) Rule, C. K.; LaMer, V. K. *J. Am. Chem. Soc.* **1938**, *60*, 1974.
(43) Bell, R. P.; Kuhn, A. T. *Trans. Faraday Soc.* **1963**, *59*, 1789.
(44) Jencks, W. P. *Catalysis in Chemistry and Enzymology*; McGraw-Hill: New York, 1969; Chapter 4.
(45) Kresge, A. J.; Rao, K. N.; Lichtin, N. N. *Chem. Ind.* **1961**, 53.
(46) Bishop, E. D. *Annu. Rep. Prog. Chem.* **1961**, *58*, 70.
(47) Tiers, G. V. D. *J. Am. Chem. Soc.* **1957**, *79*, 5585.
(48) Lewis, E. S. *Tetrahedron* **1959**, *5*, 143.
(49) Shiner, V. J. *Tetrahedron* **1959**, *5*, 243.
(50) Shiner, V. J. In *Isotope Effects in Chemical Reactions*; Collins, C. J., Bowman, N. S., Eds.; Van Nostrand Reinhold: New York, 1970; Chapter 2.
(51) Traficante, D. D.; Maciel, G. E. *J. Am. Chem. Soc.* **1965**, *87*, 4917.

cluding the addition equilibria of methanol to [1,3-$^2H_6$]-acetone and [2,2,5,5-$^2H_4$]cyclopentanone,[52] the saponification of ethyl [2-$^2H_3$]acetate,[53] ion cyclotron resonance spectroscopy studies of ion–molecule equilibria,[54] the addition of SO_3^{2-} and BH_4^- to cyclohexanones,[55] the decarboxylation and elimination of pyruvate from α-lactylthiamin,[56] the hydrolysis of acetaldehyde dimethyl acetal and ethyl vinyl ether,[57] and in the 2,3-hydride shift in the 2,3-dimethylbicyclo[2.2.2]octyl cation.[58] Most importantly, the inverse β secondary deuterium isotope effect on the ionization of carbonyl-protonated acetophenone ($K_a(CH_3)/K_a(C^2H_3) = 0.775$)[59] demonstrates that hyperconjugation is strong enough to overcome the inductive effect of deuterium substitution on acid strength.[27-30]

The possibility that hyperconjugation is responsible for the inverse secondary deuterium isotope effect on the axial water ligand ionization of $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ is quite intriguing. There is substantial experimental support for the importance of hyperconjugation in organocobalt complexes including the anomalously low acidity of (carboxymethyl)cobaloximes[60,61] and (carboxymethyl)cobalt corrinoids,[62,63] the anomalously low carbonyl stretching vibration of (formylmethyl)cobaloxime,[64] the upfield shift of the ^1H NMR resonance of the aldehyde hydrogen of (formylmethyl)cobalamin,[65] and ^{19}F NMR chemical shifts of (*p*-fluorobenzyl)cobaloximes[66-68] and in the σ-bonded (ethyl)cobaloxime carbonium ion, $^+CH_2CH_2Co(D_2H_2)L$, which is probably stabilized by hyperconjugation.[69,70] The highly successful analysis of substituent effects in (alkyl)cobaloximes of the type $YCH_2Co(D_2H_2)L$[71] using a dual-substituent parameter approach[72] including inductive and resonance effects shows that "resonance" effects are highly significant in such complexes and suggests that hyperconjugation is a general phenomenon in complexes of this type.[73] The relevant resonance hybrid is shown in **6**, in which stabilization of the negative charge on the



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metal atom must suppress the ionization of the axial water ligand. The reduced participation of this species in the deuterated analogue would thus account for the lower pK_a in this species. As in the case of carbonyl-protonated acetophenone cited above, the hyperconjugation effect evidently overwhelms the inductive effect of the α-deuterons. This phenomenon is currently under further investigation.

The presence of a significant secondary deuterium isotope effect on the ionization of the axial water ligand of $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ also suggests that Mock and Bieniarz[8] have underestimated the primary deuterium isotope effect on the base-induced decomposition of [2-$^2H_1$](2-hydroxypropyl)cobaloxime. This isotope effect was estimated by side-by-side comparison of observed rate constants for decomposition of the deuterated and undeuterated analogues, alternately, at a single basicity (0.2 M NaOH), instead of by determination of the complete dependence of the decomposition rate on hydroxide ion for each analogue. Since the deuterated analogue must be expected to be a stronger acid, a larger proportion of it will exist as the hydroxo species at a given pH than of the undeuterated analogue. As the hydroxo species are more reactive (by about 17-fold), the ratio of k^H/k^D determined by this method will be reduced from the correct value. Consideration of the data in Table I suggests that the correct primary deuterium isotope effect for [2-$^2H_1$](2-hydroxypropyl)cobaloxime should be closer to 1.1.[75] However, there is an additional complication due to the fact that Mock and Bieniarz[8] utilized the pyridine complexes in their kinetic studies. A β secondary isotope effect on the formation constant for the pyridine complex must also be anticipated. Along with the discussion above, this implies that at a given basicity, differing proportions of the deuterated and undeuterated cobaloxime will exist as the inert pyridine complex. Given these complications, it seems unwise to rely on the primary isotope effect value arising from these studies.

There are also significant inverse solvent deuterium isotope effects on the rate of decomposition of (2-hydroxyethyl)cobaloxime ($k_2^{OH^-}/k_2^{O^2H^-} = 0.28 \pm 0.01$ and $k_2^{HOH}/k_2^{^2HO^2H} = 0.37 \pm 0.11$). The Mock and Bieniarz mechanism (eq 4) is essentially an assisted, base-catalyzed E2 elimination, and such reactions are subject to inverse solvent deuterium isotope effects when the leaving group is poor ($k^{H_2O}/k^{^2H_2O} = 0.56$–$0.64$)[44,76,77] due to the fact that deuteroxide ion is a 2.12-fold stronger base than hydroxide ion (at 25 °C).[77,78] However, in this mechanism it is formation of the cis intermediate **1** which is purported to be rate-determining step. Both mechanisms require ionization of the 2-hydroxy group prior to the rate-deter-

(52) Jones, J. M.; Bender, M. L. *J. Am. Chem. Soc.* **1960**, *82*, 6322.
(53) Bender, M. L.; Feng, M. S. *J. Am. Chem. Soc.* **1960**, *82*, 6318.
(54) DeFrees, D. J.; Taagepera, M.; Levi, B. A.; Pollack, S. K.; Summerhays, K. D.; Taft, R. W.; Wolfsberg, M.; Hehve, W. J. *J. Am. Chem. Soc.* **1979**, *101*, 5532.
(55) Boyer, B.; Lamaty, G.; Roque, J. P. *Tetrahedron* **1980**, *36*, 2669.
(56) Kluger, R.; Brandl, M. *J. Am. Chem. Soc.* **1986**, *108*, 7828.
(57) Kresge, A. J.; Weeks, D. P. *J. Am. Chem. Soc.* **1984**, *106*, 7140.
(58) Siehl, H. V.; Walter, H. *J. Am. Chem. Soc.* **1984**, *106*, 5355.
(59) Arnett, E. M.; Cohen, T.; Bothner-By, A. A.; Bushick, R. D.; Sowinsky, G. *Chem. Ind.* **1961**, 473.
(60) Brown, K. L.; Zahonyi-Budo, E. *Inorg. Chem.* **1981**, *20*, 1264.
(61) Brown, K. L.; Zahonyi-Budo, E. *J. Am. Chem. Soc.* **1982**, *104*, 4117.
(62) Walker, T. E.; Hogenkamp, H. P. C.; Needham, T. E.; Matwiyoff, N. A. *J. Chem. Soc., Chem. Commun.* **1974**, 85.
(63) Brown, K. L.; Hakimi, J. M.; Huang, Y.-J. *Inorg. Chim. Acta* **1985**, *106*, 123.
(64) Silverman, R. B.; Dolphin, D. *J. Am. Chem. Soc.* **1974**, *96*, 7094.
(65) Silverman, R. B.; Dolphin, D. *J. Am. Chem. Soc.* **1976**, *98*, 4633.
(66) Dodd, D.; Johnson, M. D.; Fong, C. W. *J. Chem. Soc., Dalton Trans.* **1974**, 58.
(67) Bied-Charreton, C.; Gaudemer, A.; Chapman, C. A.; Dodd, D.; Gupta, B. D.; Johnson, M. D.; Lockman, B. C.; Septe, B. *J. Chem. Soc., Dalton Trans.* **1978**, 1807.
(68) Brown, K. L.; Lu, L.-Y. *Inorg. Chem.* **1981**, *20*, 4178.
(69) Golding, B. T.; Holland, H. L.; Horn, U.; Sakrikar, S. *Angew. Chem., Int. Ed. Engl.* **1970**, *9*, 959.
(70) Brown, K. L.; Ramamurthy, S.; Marynick, D. S. *J. Organomet. Chem.* **1985**, *287*, 377.
(71) Marzilli, L. G.; Bayo, F.; Summers, M. F.; Thomas, L. B.; Zangrando, E.; Bresciani-Pahor, N.; Mari, M.; Randaccio, L. *J. Am. Chem. Soc.* **1987**, *109*, 6045.
(72) Ehrenson, S.; Brownlee, R. T. C.; Taft, R. W. *Prog. Phys. Org. Chem.* **1973**, *10*, 1.
(73) Marzilli et al.[71] have characterized the substantial resonance effect in these compounds as reflecting n to π* conjugation between lone pairs on the group Y and the Co–C bond. However, many of the compounds successfully correlated by this approach have no Y lone pairs. The valence-bond concept of hyperconjugation accommodates all such $YCH_2Co(D_2H_2)L$ compounds, as is discussed fully elsewhere.[74]
(74) Brown, K. L.; Satayanarayana, S. Manuscript submitted to *J. Am. Chem. Soc.*
(75) There should, however, also be an α secondary deuterium isotope effect on the ionization of the β-hydroxyl of the alkyl ligand of [2-$^2H_1$](2-hydroxypropyl)cobaloxime which would lower its pK_a. As this ionization is involved in both mechanisms (i.e., eqs 2 and 4) this effect should oppose the β secondary deuterium isotope effect on the ionization of the axial water ligand. However, this effect is expected to be very small[27-30] and has a negligible effect on the correction of the primary isotope effect.
(76) Saunders, W. H.; Cockrill, A. F. *Mechanisms of Elimination Reactions*; Wiley: New York, 1973; Chapter 2.
(77) Steffa, L. J.; Thornton, E. R. *J. Am. Chem. Soc.* **1967**, *89*, 6149.
(78) Pentz, L.; Thornton, E. R. *J. Am. Chem. Soc.* **1967**, *89*, 6931.

mining step, and as pointed out above, this group would be expected to be 2.7–5.0-fold more acidic in ^2H_2O than in H_2O.[26] Since the pK_a for this ionization must be >16,[79] the increase in its acidity in ^2H_2O would be expected to be at the upper end of this range.[26,44] This effect would predict an inverse solvent deuterium isotope effect of about 0.2, in reasonably good agreement with the observed values.

The apparent kinetic isotope effect on (2-hydroxyethyl)cobaloxime decomposition upon perdeuteration of the organic ligand ($k^H/k^{^2H}$ = 1.48 for both the aquo and hydroxo species) is complex, as it may contain both primary and secondary isotope effects. For the Mock and Bieniarz mechanism (eq 4), removal of the β-proton of the organic ligand occurs only after the rate-determining step and only secondary deuterium isotope effects on the formation of the cis intermediate 1 would be expected. The hydride shift mechanism (eq 2) will be subject to both a primary isotope effect and two secondary isotope effects, an α secondary deuterium isotope effect due to the β-carbon deuteron which is not translocated (a secondary isotope effect of the first kind[28] in which the "noninvolved"[44] deuterium undergoes a spatial rearrangement; i.e., there is a change in hybridization of the carbon atom to which it is bound) and a β secondary isotope effect due to the two α deuterons (a secondary isotope effect of the second kind[28]). While it is common practice to apply the rule of thumb that in cases of complex isotope effects the primary isotope effect will be dominant,[28] this is unwise in the case of a 1,2-hydride shift reaction in which only a C–H bending mode is potentially lost in the transition state and a primary isotope effect of only 2–3 is anticipated.[44,83–85] While there has been a tendency to use a value of $k^H/k^{^2H} \sim 1.25$ for a secondary deuterium isotope effect involving an sp^3 to sp^2 hybridization change,[50] a somewhat wider variation in such values has been shown.[86] For the loss of a hydride ion from a deuterated carbon with concommitant sp^3 to sp^2 rehybridization, an α secondary deuterium isotope effect of 1.15 has been found for the reduction of 4-cyano-2,6-dinitrobenzenesulfonate by NADH.[87] If we assume such a value for the α secondary deuterium isotope effect on $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ decomposition, the observed effect would be lowered to 1.28 in the absence of the β-deuterium. However, if there is indeed significant hyperconjugation, as in **6**, this will surely decrease the reactivity of the β-hydrogens to undergo the hydride shift. Since the contribution of this resonance hybrid species will be reduced by deuteration, the β-deuterated species should be more reactive, leading to a compensatory increase in reactivity due to the α secondary isotope effect. Thus, the primary deuterium isotope effect in this system probably exceeds 1.28. For comparison, the hydride shift in the acid-catalyzed pinacol rearrangement of triphenylethylene glycol is subject to a primary deuterium isotope effect of 2.3–3.3, depending on the catalyst.[85]

Mechanism of Alkali-Induced Decomposition of (2-Hydroxyethyl)cobaloxime. Ketonization of the enol of acetaldehyde is a rapid process in aqueous base, known to occur via direct proton transfer from water to the β-carbon of the enolate anion (eq 15).[17] From the values

$$CH_2{=}CHOH + OH^- \overset{K_a^E}{\rightleftharpoons} CH_2{=}CHO^- + H_2O \xrightarrow{k_o'} CH_3CHO \quad (15)$$

reported by Chiang et al.[17] (pK_a^E = 10.50, k_o' = 8.82 × 10^2 s^{-1}) the calculated value for the rate constant for ketonization at pH 13 (i.e. the pH at which the experiment shown in Figure 3 for $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ decomposition in H_2O was performed) in 880 s^{-1} ($t_{1/2}$ = 0.8 ms). Although enol formed from $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ would be deuterated, the secondary deuterium isotope effects on the reactions in eq 15 would be expected to be small. Similarly, from the data of Capon and Zucco,[88] who studied the ketonization of enol acetaldehyde in ^2H_2O, the rate constant for ketonization at pH 13.0 (i.e. the pH at which the experiment shown in Figure 3 for $HOCH_2CH_2Co(D_2H_2)OH_2$ decomposition in ^2H_2O was performed) can be estimated to be 716 s^{-1} ($t_{1/2}$ = 1.0 ms). Consequently, under these conditions, if enol acetaldehyde were the product of the alkali-induced decomposition of (2-hydroxyethyl)cobaloximes, it would be rapidly protonated, leading to the incorporation of a hydrogen isotope from the solvent into the acetaldehyde methyl group. The data in Figure 3 show unequivocally that this is not the case. Since the hydride shift mechanism (eq 2) is the only reasonable mechanism in which the third acetaldehyde methyl proton is derived from a nonexchangeable proton on the starting material, we conclude that the alkali-induced decomposition of (2-hydroxyethyl)cobaloximes occurs via this mechanism.

The extreme difference in the course of the alkali-induced decomposition of (alkoxyethyl)- and (hydroxyethyl)cobaloximes now becomes clear. The lowest energy pathway available for decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$, the hydride shift mechanism, cannot occur for the alkoxyethyl complexes due to their inability to ionize to form the β oxy anion species, the driving force for the reaction. Being thus stable toward the hydride shift, they decompose by the only remaining pathway, i.e., the slower attack of hydroxide ion on the equatorial ligand that is common to simple $RCo(D_2H_2)OH_2$'s such as $CH_3Co(D_2H_2)OH_2$.[10]

The most attractive feature of the Mock and Bieniarz mechanism (eq 4)[8] was the ready explanation it appeared to provide for the inertness of the $HOCH_2CH_2Co(D_2H_2)L$ complexes; i.e. the axial ligand prevents formation of the cis intermediate **2**. However, in the base-induced decomposition of (methyl)cobaloximes (Scheme I),[10] all $CH_3Co(D_2H_2)L$ species studied were also inert (except for L = OH^-), indicating that such inertness of $RCo(D_2H_2)L$ complexes to base-induced decomposition is a more general phenomenon requiring a more general explanation.

The enhanced reactivity of $HOCH_2CH_2Co(D_2H_2)OH^-$ relative to the aquo complex (Table I) is surprising, since migration of a hydride ion from the β- to the α-carbon would be expected to be disfavored by the negative charge on the former chelate. However, again, the base-induced decomposition of $CH_3Co(D_2H_2)OH_2$ (Scheme I), which

(79) The pK_a of ethanol has been reported to be 15.83–16.0.[80–83] Since the cobaloxime cobalt center is known to be exceedingly electron donating,[60,68] the pK_a of (2-hydroxyethyl)cobaloximes must be expected to be higher.

(80) Ballinger, P.; Long, F. A. *J. Am. Chem. Soc.* **1960**, *82*, 795.
(81) Takahishim, S.; Cohen, L. A.; Miller, H. K.; Peake, E. G. *J. Org. Chem.* **1971**, *36*, 1205.
(82) Murto, J. *Acta Chem. Scand.* **1964**, *18*, 1403.
(83) Hawthorne, M. F.; Lewis, E. S. *J. Am. Chem. Soc.* **1958**, *80*, 4296.
(84) Winstein, S.; Takahashi, J. *Tetrahedron Lett.* **1955**, *2*, 316.
(85) Collins, C. J.; Rainey, W. T.; Smith, W. B.; Kaye, I. A. *J. Am. Chem. Soc.* **1959**, *81*, 460.
(86) Kirsh, J. F. In *Isotope Effects on Enzyme Catalyzed Reactions*; Cleland, W. W., O'Leary, M. H., Northrop, D. B., Eds.; University Park Press: Baltimore, 1977; p 100.
(87) Kurtz, L. C.; Frieden, C. *J. Am. Chem. Soc.* **1980**, *102*, 4198.
(88) Capon, B.; Zucco, C. *J. Am. Chem. Soc.* **1982**, *104*, 7567.
(89) From the data of Bunton and Shiner.[26] pK_a^E can be estimated to be 11.08 in ^2H_2O. Using Capon and Zucco's data[88] for the ketonization of enol acetaldehyde in ^2H_2O, k_o' (eq 15) can then be estimated to be 725 s^{-1} in ^2H_2O. Thus, the solvent deuterium isotope effect on k_o' ($k_o'(H_2O)/k_o'(^2H_2O)$) is small (1.2), suggesting limited proton transfer in the transition state (since $K_a(H_2O)/K_a(^2H_2O)$ for water is 6.5).[26]

occurs via attack of hydroxide ion on the equatorial ligand, serves as a precedent, since only the hydroxo species is reactive (the aquo species is at least 140-fold less reactive).[10] In the case of the (2-hydroxyethyl)cobaloximes, the excess reactivity of the hydroxo species could be due to hyperconjugation, as shown in the resonance hybrid **6**, since the hyperconjugated resonance contributor will clearly be less reactive toward the 1,2-hydride shift. As this hyperconjugative interaction also places negative charge on the metal atom, ionization of the axial water ligand would be expected to destabilize this resonance contributor, thus enhancing hydride shift reactivity. Indeed, the greater reactivity of the hydroxo species may indicate the importance of hyperconjugation in this system.

Summary. The kinetics of the alkali-induced decomposition of (2-hydroxyethyl)cobaloxime have been shown to be consistent with a simple scheme in which both the aquo and hydroxo species decompose, with the latter being about 20-fold more reactive. Despite the fact that the measured rate constants for base-catalyzed exchange of acetaldehyde methyl protons with solvent deuterons and those for the exchange of the methyl deuterons of perdeuterioacetaldehyde with solvent protons exceed the rate constants for decomposition of $HOCH_2CH_2Co(D_2H_2)OH_2$ in ^2H_2O and of $HOC^2H_2C^2H_2Co(D_2H_2)OH_2$ in H_2O, respectively, under all conditions, it was nonetheless possible to determine the isotopic composition of the nascent acetaldehyde from both decomposition reactions. This was accomplished by quenching the decomposition reaction at various times and converting the product acetaldehyde to its oxime for isotopic analysis by MS. The results unequivocally show that the acetaldehyde formed obtains its third methyl proton (or deuteron) from starting material and not from solvent. This eliminates any mechanism which directly forms the enol of acetaldehyde and strongly suggests that acetaldehyde is formed from (2-hydroxyethyl)cobaloximes in aqueous base by a 1,2-hydride shift mechanism.

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Tricarbon Carborane Chemistry. 1. Syntheses and Structural Characterizations of Monocage Iron, Manganese, and Nickel Metallatricarbaborane Complexes

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Improvements in the route to the tricarbon carborane 6-CH_3-5,6,9-$C_3B_7H_{10}$ (**1**) and its corresponding monoanion, 6-CH_3-5,6,9-$C_3B_7H_9^-$, have enabled the syntheses of a series of monocage iron, manganese, and nickel tricarbaborane complexes that are analogues of the cyclopentadienyl complexes of these metals. Reaction of 6-CH_3-5,6,9-$C_3B_7H_9^-$ with (η-C_5H_5)Fe(CO)$_2$I gave two isomeric products, 1-(η-C_5H_5)Fe-2-CH_3-2,3,4-$C_3B_7H_9$ (**2**) and 1-(η-C_5H_5)Fe-4-CH_3-2,3,4-$C_3B_7H_9$ (**3**), while reaction of the anion with Mn(CO)$_5$Br yielded 1-(CO)$_3$Mn-2-CH_3-2,3,4-$C_3B_7H_9$ (**4**). Single-crystal X-ray structural determinations of **2** and **3** confirm that they are hybrid complexes in which an iron atom is sandwiched between cyclopentadienyl and tricarbon carborane ligands. The ferratricarbaborane cages in both **2** and **3** have closo-octadecahedral structures, consistent with their 24-skeletal-electron counts, with the iron atom in the six-coordinate position and two of the cage carbon atoms in four-coordinate positions adjacent to the iron. The two structures differ in the position of the exopolyhedral methyl group. In **2** the methyl group is bound to a four-coordinate carbon as in **1**. In **3** the methyl group has rearranged to an adjacent five-coordinate cage carbon. The reaction of 6-CH_3-5,6,9-$C_3B_7H_9^-$ with [(η-C_5H_5)NiCO]$_2$ yielded the compound 9-(η-C_5H_5)Ni-8-CH_3-7,8,10-$C_3B_7H_9$ (**5**), which is proposed, on the basis of its skeletal-electron count and the spectroscopic data, to have a sandwich structure in which the nickelatricarbaborane cage has an open-cage geometry based on an icosahedron missing one vertex.

Introduction

Tricarbon carboranes have been a largely unexplored class of boron cage compounds. The first tricarbon carboranes, the *C*-methyl and *C,C'*-dimethyl derivatives of *nido*-2,3,4-$C_3B_3H_7$, were isolated by Grimes[1] in 1966 from the reaction of B_4H_{10} and acetylene. Initial investigations[2] of the metal chemistry of this cage system yielded the first tricarbaborane complexes, (η^1-2,3,4-$Me_2C_3B_3H_5$)Mn(CO)$_5$ and (η^5-2,3,4-$Me_2C_3B_3H_4$)Mn(CO)$_3$; however, the parent carborane could not be prepared on scales sufficient for more extensive chemical investigations. Recently Siebert[3]

(1) (a) Bramlett, C. L.; Grimes, R. N. *J. Am. Chem. Soc.* **1966**, *88*, 4269–4270. (b) Grimes, R. N.; Bramlett, C. L. *J. Am. Chem. Soc.* **1968**, *89*, 2557–2560. (c) Franz, D. A.; Grimes, R. N. *J. Am. Chem. Soc.* **1971**, *93*, 387–394.

(2) (a) Howard, J. M.; Grimes, R. N. *J. Am. Chem. Soc.* **1969**, *91*, 6499–6500. (b) Howard, J. M.; Grimes, R. N. *Inorg. Chem.* **1972**, *11*, 263–267.

(3) (a) Kuhlmann, T.; Pritzkow, H.; Zenneck, U.; Siebert, W. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 965–966. (b) Zwecker, J.; Pritzkow, H.; Zenneck, U.; Siebert, W. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 1099–1100. (c) Zwecker, J.; Kuhlmann, T.; Pritzkow, H.; Siebert, W.; Zenneck, U. *Organometallics* **1988**, *7*, 2316–2324. (d) Siebert, W.; Schafer, V.; Brodt, G.; Fessenbecker, A.; Pritzkow, H. *Abstracts of Papers*, 200th National Meeting of the American Chemical Society, Washington, DC, Aug 1990; American Chemical Society: Washington, DC, 1990; INOR 381.

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