Mechanism of Base-Catalyzed Methane Formation from Methyl(aquo)cobaloxime[1-3]

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Abstract: The formation of methane in aqueous base from methylcobaloximes and some analogues has been studied by GLC, mass spectral, and manometric techniques. Decomposition of methyl(aquo)cobaloxime in D_2O (1.0 N NaOD) yielded monodeuteriomethane, while trideuteriomethyl(aquo)cobaloxime gave trideuteriomethane in H_2O (1.0 N KOH) and tetradeuteriomethane in D_2O (1.0 N NaOD). In all cases (in 1.0 N base) the yield was less than stoichiometric (ca. 70%) but additional methane was obtained by photolysis indicating formation of a methylcobalt side product. Studies of the dependence of the rate and yield of methane formation on $[OH^-]$ (50 °C, ionic strength 1.0 M) showed that only the hydroxo complex of methylcobaloxime is reactive for methane formation, and both methane and side product formation are first order in $[OH^-]$. The second-order rate constants for methane formation were determined to be zero and 1.36×10^{-4} M^{-1} s^{-1} while those for side-product formation were 7.47×10^{-5} and 5.52×10^{-5} M^{-1} s^{-1} for the aquo and hydroxo complexes, respectively. Studies of the dependence of the rate constant for methane formation on the concentration of four different Lewis base axial ligands (including sulfur and nitrogen donors, with affinity for the cobalt center varying from 6.06 to 3500 M^{-1}) showed that the N- and S-liganded species are at least four orders of magnitude less reactive than the hydroxo complex. The cobalt-containing dealkylated product of this cleavage reaction was found, after neutralization of reaction mixtures, to be a cobaloxime analogue in which one Schiff's base linkage has become hydrated. This material was reconverted to a cobaloxime upon stirring in aqueous acid. The methylcobalt side product proved to be extremely labile and all attempts to isolate it led to its reversion to starting material. These observations are discussed in the framework of several ionic mechanisms, although a homolytic mechanisms cannot be ruled out.

Introduction

It is widely stated that organocobalt complexes can undergo carbon–cobalt bond dissociation by any of three primary cleavage mechanisms denoted here as cleavage modes I, II, and III.[5-9]

$$\text{mode I} \qquad \text{R-Co(Chel)} \rightarrow [\text{R}^+] + \text{Co}^{\text{I}}\text{(Chel)} \tag{1}$$

$$\text{mode II} \qquad \text{R-Co(Chel)} \rightarrow [\text{R}\cdot] + \text{Co}^{\text{II}}\text{(Chel)} \tag{2}$$

$$\text{mode III} \qquad \text{R-Co(Chel)} \rightarrow [\text{R}^-] + \text{Co}^{\text{III}}\text{(Chel)} \tag{3}$$

Examples of mode I cleavage include the base-catalyzed formation of substituted olefins and Co(I) complexes from organocobaloximes,[10] cobalamins,[11] and pentacyanocobaltates[12] with electron-withdrawing β substituents (via β-elimination of Co(I)) and the base-catalyzed formation of carbonyl compounds and Co(I) complexes from 2-hydroxyalkylcobalt complexes[11b,12] (supposedly via a 1,2-hydride shift). Examples of mode II cleavages include photolysis of methylcobalt complexes,[4,14] and 5′-deoxyadenosylcobalamin[14j,15] (photolysis of other organocobalt complexes containing proton-bearing β carbons may proceed via concerted elimination of H–Co^{I}(chelate) under certain conditions[16]) and the "activation" of 5′-deoxyadenosylcobalamin during the catalytic cycle of certain B_{12}-requiring enzymes.[17] Examples of mode III cleavage include acid-catalyzed formation of olefins from β-hydroxy-, β-alkoxy-, β-acetoxy-, and β-ketoalkylcobalt complexes including cobaloximes,[13,18] cobalamins,[7,13,19] and pentacyanocobaltates.[12a,20]

This report describes a study of an apparent example of mode III cleavage for a simple, unactivated organocobalt complex (i.e., one without a leaving group β to cobalt), namely, the base-catalyzed heterolysis of methyl(aquo)cobaloxime to produce methane.[3,21] These results confirm the suggestive evidence of myself and others[22] that all simple alkyl(aquo)cobaloximes undergo carbon–cobalt bond cleavage in aqueous base with generation of a cobalt(III) complex.

Experimental Section

Materials. Cobaltous chloride, cobaltous acetate, sodium borohydride, sodium and potassium hydroxide, potassium chloride, potassium nitrate, methanol, diethyl ether, boron trifluoride etherate, dimethylglyoxime, diphenylglyoxime, and methyl iodide were obtained in the highest purity commercially available and used without further purification. Deuterium oxide (99.8 atom % D) and sodium deuteroxide (40% solution in D_2O, 99+ atom % D) were from Aldrich. Trideuteriomethyl iodide (99.5 atom % D) was from Stohler Isotopes. Pyridine, dimethoxyethylamine, *S*-methylmercaptoethanol, and 2-mercaptoethanol were redistilled under argon and stored in the dark over type 4A molecular sieve, under argon. Glass-distilled deionized water was used throughout.

$CH_3Co(D_2H_2)HOH$ was synthesized by a modification of the procedure of Crumbliss and Gaus[23] as follows: 12.45 g of cobaltous acetate tetrahydrate (0.05 mol) and 11.61 of g dimethylglyoxime (0.10 mol) were stirred under argon in 200 mL of deoxygenated methanol for 1 h. Following addition of 6.67 g of KOH (0.102 mol) in about 20 mL of deoxygenated water, the reaction mixture was cooled in ice and 7.81 g of methyl iodide (0.055 mol) was added. A total of 1.20 g of sodium borohydride in about 40 mL of deoxygenated water (plus 0.10 g of KOH) was added dropwise over a period of about 1 h with vigorous stirring after which thin layer chromatography of a small sample on silica gel showed that formation of the product was essentially complete. The reaction mixture was filtered, evaporated to about 100 mL, diluted with 100 mL of water, and stored at 4 °C overnight. Suction filtration provided 12.20 g of red crystals which were dried over P_2O_5 under vacuum. Addition of 2 mL of pyridine followed by cooling in ice and suction filtration provided 2.61 g of $CH_3Co(D_2H_2)py$, combined yield 0.0447 mol, 89%. Anal.[24] Co, C, H, N. NMR ($CDCl_3$-methanol-d_4): $\delta_{\mathrm{Me_4Si}}$ 0.74 (s, 2.94 H), 2.22 (s, 12.0 H).

$CD_3Co(D_2H_2)HOH$ was prepared analogously using trideuteriomethyl iodide in place of methyl iodide.

$CH_3Co(D_2B_2F_4)HOH$ was prepared from $CH_3Co(D_2H_2)HOH$ and boron trifluoride etherate as described by Cartaño and Ingraham,[25] yield 75%. Anal. C, H, N, F. NMR (Me_2SO-d_6): $\delta_{\mathrm{Me_4Si}}$ 0.91 (s, 2.90 H), 2.32 (s, 12.0 H).

$CH_3Co(P_2H_2)py$ was synthesized by the procedure of Schrauzer[26] for the analogous cobaloxime and was purified by silica gel chromatography, yield 20%. Anal. C, H, N. NMR ($CDCl_3$): $\delta_{\mathrm{Me_4Si}}$ 1.44 (s, 3.1 H), 6.95–9.08 (m, 25.0 H).

$CH_3Co(P_2H_2)HOH$ was obtained by hydrolysis of the pyridine complex with Bio-Rad AG 50W-X8 ion exchange resin (H^+ form) as has been described for the cobaloximes.[27] Anal. C, H, N. NMR ($CDCl_3$-Me_2SO-d_6): $\delta_{\mathrm{Me_4Si}}$ 1.20 (s, 2.90 H), 7.07–7.43 (m, 20.0 H).

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$H[Co(D_2H_2)Cl_2]$ was prepared by the method of Ablov and Samus.[28] Anal. C, H, N, Cl. NMR (Me_2SO-d_6): δ_{Me_4Si} 2.36 (s, 12.0 H).

Methods. All manipulations with methylcobalt complexes were performed in dim light and solutions were covered with aluminum foil whenever possible. Ionic strength was maintained at 1.0 M with KCl or KNO_3.

The apparent dissociation constant, $K_D{}^{OH^-}$, for hydroxide ion from $CH_3Co(D_2H_2)OH^-$ (eq 4, 5) was determined at 50.0 ± 0.1 °C, ionic strength 1.0 M (KNO_3), by spectrophotometric titration at 455 nm using a Gilford Model 250 spectrophotometer by the method which has been described.[29]

$$\mathrm{CH_3Co(D_2H_2)OH^-} \underset{\pm\mathrm{OH^-}}{\overset{K_D{}^{\mathrm{OH^-}}}{\rightleftharpoons}} \mathrm{CH_3Co(D_2H_2)HOH + OH^-} \qquad (4)$$

$$K_D{}^{\mathrm{OH^-}} = [\mathrm{CH_3Co(D_2H_2)HOH}][\mathrm{OH^-}]/[\mathrm{CH_3Co(D_2H_2)OH^-}] \qquad (5)$$

NMR spectra were obtained on a Varian T-60 NMR spectrometer.

GLC experiments were performed on a Perkin-Elmer MKII gas chromatograph equipped with a 10 ft × ⅛ in. Porapak Q column. At a column temperature of 50 °C, carrier flow 37.5 mL/min, the retention time for methane was 52 s.

Mass spectral measurements were made on a Finnigan 3200 GC/MS at an ionizing potential of 70 eV. Mass spectral samples (total volume 10 mL) contained 1.67×10^{-3} M cobaloxime and 1.0 N aqueous base. They were placed in glass bulbs fitted with high-vacuum Teflon stopcocks, frozen in liquid nitrogen, evacuated to 5×10^{-3} Torr, sealed, and allowed to thaw. The freeze-pump-thaw cycle was repeated twice. The samples were then incubated in the dark at 50 °C for 16 h, frozen in liquid nitrogen, and the atmosphere above the frozen sample was vented directly into the mass spectrometer's gas inlet.

The experiment to confirm methane as the photolysis product was performed as follows. Two samples (10 mL, 3.41×10^{-3} M in cobaloxime, 1.0 N in KOH) were prepared as described above and incubated for 19 h at 50 °C in the dark. The samples were then frozen, evacuated to 1×10^{-2} Torr, sealed, and allowed to thaw. The freeze-pump-thaw cycle was repeated twice. One sample was then photolyzed for 25.5 h with a 275-W tungsten lamp at a distance of 10 cm, while the control was maintained dark at room temperature. Mass spectral analysis of both samples was performed as described above (inlet pressure 5×10^{-7} Torr).

Manometric experiments were performed in Warburg manometers with a Precision Seven Unit Warburg Apparatus (Model 66670). Bath temperatures were maintained within ±0.1 °C. Manometers and 15-mL reaction flasks were calibrated using the ferricyanide–hydrazine method.[30] Aqueous (or D_2O) solutions of KOH (or NaOD), KCl or KNO_3 (when appropriate), and ligand (when appropriate) were placed in the main compartment and aqueous solutions of methylcobalt complex were placed in the side arm of the reaction flasks (typical volumes 4.2 mL in main compartment, 0.8 mL in side arm). The manometers were then mounted on the bath and shaken slowly for at least 1 h, during which time a continuous stream of argon or nitrogen (scrubbed with a vanadous sulfate-zinc gas train[31]) was passed through each manometer. The manometer stopcocks were then closed and the manometers incubated for an additional 30 min to ensure thermal equilibrium before mixing the side-arm contents with the main compartment. Corrections for changes in atmospheric pressure were made by use of a thermobarometer.[32]

For all experiments in which hydroxide ion concentration was varied, and for all experiments with ligands at <90% saturation of the ligand binding equilibrium, the reactions were followed manometrically to completion. Volumes of methane generated (at STP) were calculated from the flask constant for each manometer-flask combination and plots of ln ($V_\infty - V_t$) vs. t were constructed where V_∞ is the volume of methane released after completion ($>6T_{1/2}$) and V_t is the volume released at time t. Such plots were linear for 3 half-times. The first-order rate constants for starting material disappearance, k_{obsd}, were obtained from the slopes of these plots and the yield from the intercepts. After completion of each reaction, the reaction mixtures were photolyzed for 24 h with the two 750-lm fluorescent tubes positioned below the transparent bath bottom and two 275-W incandescent lamps positioned above the bath.

For experiments in which ligands were present in sufficient concentration to ensure the formation of $CH_3Co(D_2H_2)L$ to >90% completion (i.e., $T_{1/2} > 12$ h) the method of initial rates was used.[33] The main compartment contained aqueous KOH (1.0 N) and ligand as before, but the side arm contained solid $CH_3Co(D_2H_2)HOH$ (ca. 18 mg) such that after mixing the final cobaloxime concentration was ca. 0.01 M. The reactions were followed for the first 5% of the expected gas evolution (ca. 50–70 µL) and the rate of gas evolution was obtained from the slopes of plots of V_t vs. time. First-order rate constants were obtained by dividing the rates of gas evolution by the expected yield based on the weight of cobaloxime employed and the observed average percentage yield for all reactions with that ligand which were followed to completion (average yields ca. 70%).

Preparation of Cobalt-Containing Products. $CH_3Co(D_2H_2)HOH$ (2.0 g, 0.0064 mol) was dissolved in 100 mL of deoxygenated 1.0 N aqueous KOH and stirred under argon for 22 h at 50 °C. The reaction mixture was acidified to pH 5 with concentrated H_2SO_4, lyophilized, and dried over P_2O_5 under vacuum. The solid was continuously extracted with a total of 400 mL of chloroform for 4 days. The dark brown extract was evaporated to dryness and the resulting solid dried over P_2O_5 under vacuum (wt 2.02 g). The solid was dissolved in ca. 10 mL of chloroform and applied to a 3.8 × 52 cm column of silica gel (in chloroform). The column was washed with 250 mL of chloroform and then a red fraction was eluted with ca. 350 mL of acetone. A brown fraction was then eluted with 500 mL of methanol plus 500 mL of water. Evaporation of the acetone fraction produced 378 mg of red powder that was chromatographically identical with $CH_3Co(D_2H_2)HOH$ on silica gel thin layers in three solvents ($CHCl_3$, acetone, methanol), yield 19% (as $CH_3Co(D_2H_2)HOH$). Anal. C, H, N. NMR ($CDCl_3$-methanol-d_4): δ_{Me_4Si} 0.74 (s, 3.02 H), 2.22 (s, 12.0 H). The methanol–water fraction was evaporated to dryness and dried over P_2O_5 under vacuum, yield 68% (as compound **1**). This material was recrystallized from methylene chloride–cyclohexane to yield a brown powder. Anal. Calcd for $CoC_8H_{19}N_4O_7$ (compound **1**): Co, 17.22; C, 28.08; H, 5.60; N, 16.37; O, 32.73. Found: Co, 17.19; C, 28.24; H, 5.37; N, 16.21; O, 33.00. NMR: see Figure 5 and discussion.

Conversion of Compound 1 to $H[Co(D_2H_2)Cl_2]$. **1** (above) (0.54 g, 0.0015 mol) was stirred overnight in 25 mL of 20% aqueous HCl at room temperature in the dark. The resulting suspension was filtered by suction to obtain 0.36 g of gray-green powder, yield 67% (as $H[Co(D_2H_2)Cl_2]$). Anal. Calcd for $CoC_8H_{15}N_4O_4Cl_2$: Co, 16.32; C, 26.61; H, 4.19; N, 15.52; O, 17.72; Cl, 19.64. Found: Co, 16.42; C, 26.58; H, 4.43; N, 15.50; O, 17.77; Cl, 19.30. NMR (Me_2SO-d_6): δ_{Me_4Si} 2.36 (s, 12.0 H).

Results and Discussion

Organic Product. Methane was detected in the inert atmosphere above solutions of $CH_3Co(D_2H_2)HOH$ in 1.0 N aqueous base at 50 °C both by GLC and mass spectral analysis. In addition, GLC analysis showed that methane was also formed in reaction mixtures incubated under air. When the solvent was D_2O (1.0 N NaOD) the product was monodeuteriomethane of high isotopic purity (Table I). When $CD_3Co(D_2H_2)HOH$ was decomposed in 1.0 N aqueous KOH, trideuteriomethane was obtained, while in D_2O (1.0 N NaOD) tetradeuteriomethane was the product (Table I).

Methane formation was quantitated manometrically using Warburg manometers under anaerobic conditions. In all cases the yields of methane were less than stoichiometric, the average yield for $CH_3Co(D_2H_2)HOH$ in aqueous 1.0 N KOH being 68.8 ± 2.6% (average of nine determinations). Neither the yield nor the apparent first-order rate constant for methylcobaloxime disappearance at 50 °C (k_{obsd}) was significantly dependent on total cobaloxime concentration over the range ca. 5.0×10^{-4} to 5.0×10^{-3} M. Lowering the temperature to 25 °C also had no effect on the yield of methane (Table I). However, in all experiments, subsequent photolysis produced an additional amount of methane (identified by its mass spectrum) such that the combined base-catalyzed and photolytic yields were essentially stoichiometric (Table I). These observations indicate that the base-catalyzed reaction does not convert significant amounts of the organic ligand to any product other than methane.

$CH_3Co(D_2B_2F_4)HOH$ was cleaved in 1.0 N aqueous KOH

Table I. Products, Yields, and Rate Constants for the Formation of Methane from Methylcobalt Chelates in 1.0 N Aqueous Base under an Inert Atmosphere

compd	concn, M	temp °C	base (solvent)	product	min isotopic[a] purity, %	k_{obsd}, s^{-1}	base-cat.[b] yield, %	photolysis[b] yield, %	total[c] yield, %
$CH_3Co(D_2H_2)HOH$	1.68×10^{-3}	50	KOH (H_2O)	CH_4		$1.86 \pm 0.14 \times 10^{-4}$ [d]	68.6 ± 2.7[d]	23.8 ± 2.0	92.4 ± 4.7
$CH_3Co(D_2H_2)HOH$	4.97×10^{-4}	50	KOH (H_2O)	CH_4	—	$1.84 \pm 0.09 \times 10^{-4}$	73.1 ± 2.4		
$CH_3Co(D_2H_2)HOH$	5.00×10^{-3}	50	KOH (H_2O)	CH_4		$1.83 \pm 0.03 \times 10^{-4}$ [e]	68.7 ± 3.0[e]	23.3 ± 0.9	92.0 ± 3.9
$CH_3Co(D_2H_2)HOH$	1.67×10^{-3}	25	KOH (H_2O)	CH_4		$2.55 \pm 0.08 \times 10^{-5}$	66.6 ± 2.0		
$CH_3Co(D_2H_2)HOH$	1.67×10^{-3}	50	NaOD (D_2O)	CDH_3	94	$7.76 \pm 0.34 \times 10^{-5}$ [e]	77.1 ± 1.4[e]	19.4 ± 0.7	96.5 ± 2.1
$CD_3Co(D_2H_2)HOH$	1.67×10^{-3}	50	KOH (H_2O)	CD_3H	95	$1.47 \pm 0.06 \times 10^{-4}$	69.7 ± 1.7	27.3 ± 3.5	97.0 ± 5.2
$CD_3Co(D_2H_2)HOH$	1.67×10^{-3}	50	NaOD (D_2O)	CD_4	94	$1.13 \pm 0.02 \times 10^{-4}$	70.5 ± 0.4	27.9 ± 1.9	98.4 ± 2.3
$CH_3Co(D_2B_2F_4)HOH$	2.01×10^{-3}	50	KOH (H_2O)	CH_4		$3.03 \pm 0.05 \times 10^{-6}$ [e]	78.1 ± 1.8[e]		

[a] By mass spectral analysis. [b] From manometric experiments. [c] Sum of the base-catalyzed and photolysis yields. [d] Average of nine determinations. [e] Average of two determinations.

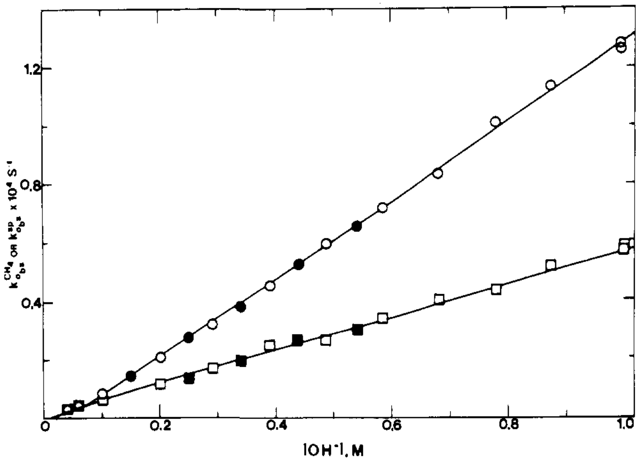
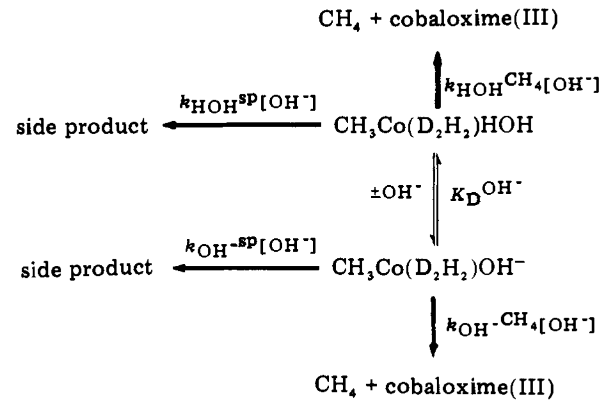


Figure 1. Plots of $k_{obsd}^{CH_4}$ (● and ○) and k_{obsd}^{sp} (■ and □) vs. $[OH^-]$ for methylcobaloxime at 50.0 °C. Ionic strength was maintained at 1.0 M with KCl (solid symbols) or KNO_3 (open symbols). The solid lines were calculated from eq 8 and 9 and the values $k_{HOH}^{CH_4} = 0$; $k_{OH}^{CH_4} = 1.36 \pm 0.03 \times 10^{-4}$ M^{-1} s^{-1}; $k_{HOH}^{sp} = 7.47 \pm 0.42 \times 10^{-5}$ M^{-1} s^{-1}; $k_{OH^-}^{sp} = 5.52 \pm 0.50 \times 10^{-5}$ M^{-1} s^{-1}; $K_D^{OH} = 0.0642 \pm 0.0025$ M.

Scheme I



about 60-fold more slowly than $CH_3Co(D_2H_2)HOH$ to give methane in 78% yield (Table I). However, $CH_3Co(P_2H_2)HOH$ was significantly less reactive, producing only a 9.4 ± 1.0% yield of methane after 284 h at 50 °C in 1.0 N KOH.

These results show that $CH_3Co(D_2H_2)HOH$ is cleaved heterolytically presumably to a cobaloxime(III) complex (in agreement with earlier spectrophotometric results[22]) and a methyl carbanion (or carbanion-like fragment) which is protonated by solvent. In addition, a yield-limiting side reaction occurs which converts a significant amount of starting material to a photolabile but base-stable methylcobalt complex, presumably by some base-induced alteration of the equatorial ligand system. Results in Table I show that this side reaction is not second order in $CH_3Co(D_2H_2)HOH$.

Kinetics. Dependence on Hydroxide Ion. First-order rate constants (k_{obsd}) and yields for the base-catalyzed reaction were determined manometrically for $CH_3Co(D_2H_2)HOH$ at 50.0 °C over a range of [KOH] from 0.06 to 1.0 N. Ionic strength was maintained at 1.0 M with KCl or KNO_3 and all reactions were followed to completion. The data were analyzed according to the most general scheme (Scheme I) which allows for base-catalyzed reaction of the two principal species present, $CH_3Co(D_2H_2)HOH$ and $CH_3Co(D_2H_2)OH^-$. At a given hydroxide concentration the parallel pseudo-first-order reaction system leads to the rate law of eq 6 for methane formation[34]

$$[CH_4] = (k_{obsd}^{CH_4}[\text{methylcobaloxime}]/k_{obsd})(1 - e^{-k_{obsd}t}) \qquad (6)$$

where $k_{obsd}^{CH_4}$ is the observed pseudo-first-order rate constant for methane formation and k_{obsd} is that for the disappearance of starting material. Since eq 7 also applies[34]

$$k_{obsd} = k_{obsd}^{CH_4} + k_{obsd}^{sp} \qquad (7)$$

the slopes and intercepts of the first-order plots from manometric data allow the calculation of $k_{obsd}^{CH_4}$ and k_{obsd}^{sp} whose dependence on hydroxide ion concentration is shown in Figure 1. From Scheme I and the law of mass action, the rate laws of eq 8 and 9 are readily derived.

$$k_{obsd}^{CH_4} = (k_{HOH}^{CH_4}K_D^{OH^-}[OH^-] + k_{OH}^{CH_4}[OH^-]^2)/([OH^-] + K_D^{OH^-}) \qquad (8)$$

$$k_{obsd}^{sp} = (k_{HOH}^{sp}K_D^{OH^-}[OH^-] + k_{OH^-}^{sp}[OH^-]^2)/([OH^-] + K_D^{OH^-}) \qquad (9)$$

Dividing by hydroxide ion concentration provides eq 10 and 11 for the dependence of the apparent second-order rate constants ($k_2^{CH_4} = k_{obsd}^{CH_4}/[OH^-]$ and $k_2^{sp} = k_{obsd}^{sp}/[OH^-]$) on hydroxide ion concentration.

$$k_2^{CH_4} = (k_{HOH}^{CH_4}K_D^{OH^-} + k_{OH}^{CH_4}[OH^-])/([OH^-] + K_D^{OH^-}) \qquad (10)$$

$$k_2^{sp} = (k_{HOH}^{sp}K_D^{OH^-} + k_{OH^-}^{sp}[OH^-])/([OH^-] + K_D^{OH^-}) \qquad (11)$$

Plots of $k_2^{CH_4}$ and k_2^{sp} vs. $[OH^-]$ (Figure 2A) show the predicted hyperbolic dependence. These data were analyzed by transformation of eq 10 and 11 to

$$k_2^{CH_4} = k_{HOH}^{CH_4} + (k_{OH}^{CH_4} - k_{HOH}^{CH_4})\alpha \qquad (12)$$

$$k_2^{sp} = k_{HOH}^{sp} + (k_{OH^-}^{sp} - k_{HOH}^{sp})\alpha \qquad (13)$$

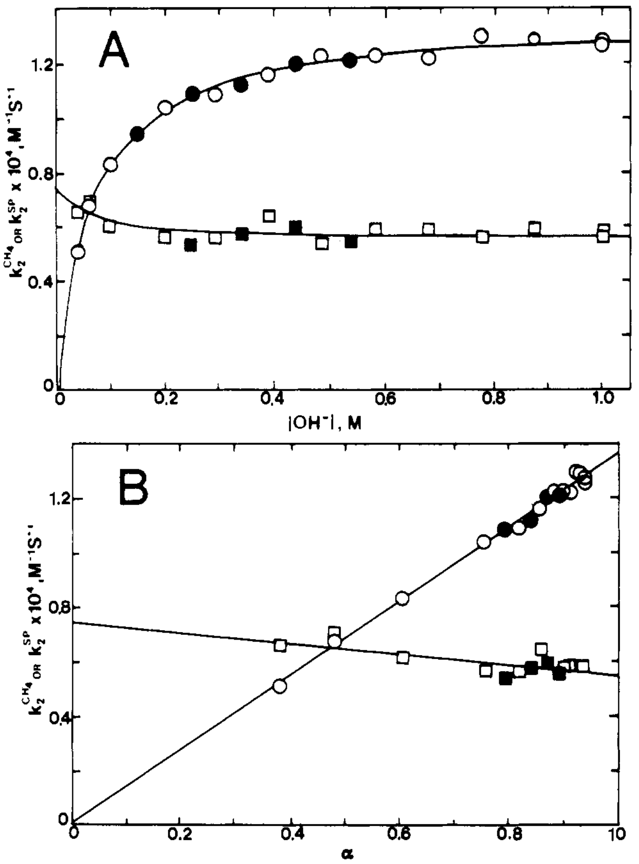


Figure 2. (A) Plots of $k_2^{CH_4}$ (● and ○) and k_2^{sp} (■ and □) vs. $[OH^-]$ for methylcobaloxime at 50.0 °C. Ionic strength was maintained at 1.0 M with KCl (solid symbols) or KNO_3 (open symbols). The *solid lines* were calculated from eq 10 and 11 and the values of the rate and equilibrium constants given in the legend to Figure 1. (B) Plots of $k_2^{CH_4}$ (● and ○) and k_2^{sp} (■ and □) vs. α (eq 14) for methylcobaloxime at 50.0 °C. Ionic strength was maintained at 1.0 M with KCl (solid symbols) or KNO_3 (open symbols). The *solid lines* are least-squares regression lines.

in which α is the fraction of cobaloxime as the hydroxo species:

$$\alpha = [OH^-]/([OH^-] + K_D^{OH^-}) \quad (14)$$

Values of α were calculated from eq 14 and the spectrophotometrically determined value of $K_D^{OH^-}$ at 50 °C (0.0642 ± 0.0025 M). Plots of $k_2^{CH_4}$ and k_2^{sp} vs. α (Figure 2B) were satisfactorily linear over the range α = 0.38-0.94. Least-squares fits of these data provided the values $k_{OH}{}^{CH_4} = 1.36 \pm 0.03 \times 10^{-4}$ M^{-1} s^{-1} and $k_{HOH}{}^{CH_4} = 9.65 \pm 24.2 \times 10^{-7}$ M^{-1} s^{-1} for methane formation and $k_{OH^-}{}^{sp} = 5.52 \pm 0.50 \times 10^{-5}$ M^{-1} s^{-1} and $k_{HOH}{}^{sp} = 7.47 \pm 0.42 \times 10^{-5}$ M^{-1} s^{-1} for side product formation. Hence, only the hydroxo complex is appreciably reactive for base-catalyzed methane formation, although both the aquo and hydroxo species undergo side-product formation with comparable reactivities.

Kinetics. Dependence on Ligands. The dependence of the observed rate constant for methane formation on the concentration of four ligands (py, DEA, SMME, 2-ME) at 50.0 °C in 1.0 N KOH is shown in Figure 3. These results were analyzed in terms of Scheme II, in which no attempt has been made to account for the reactivities of the various ionic species since all experiments were conducted in 1.0 N KOH. Application of the law of mass action leads to

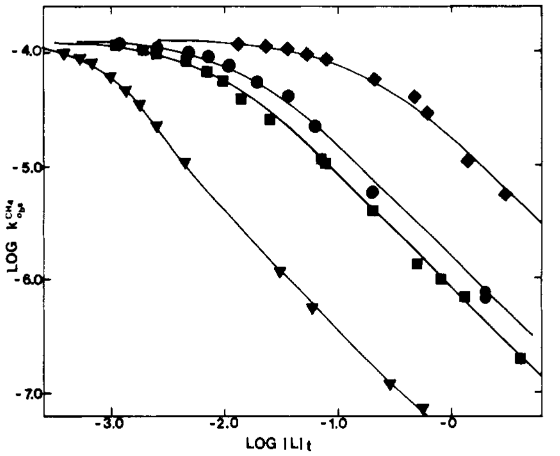


Figure 3. Plots of log $k_{obsd}{}^{CH_4}$ for methane formation at 50.0 °C in 1.0 N KOH vs. log $[L]_t$ for the ligands SMME (◆), py (●), DEA (■), and 2-ME (▼). The *solid lines* were calculated from eq 15 and 17, the values of $K_f{}^{app}$ in Table II, $k_{aquo}{}^{CH_4} = 1.28 \times 10^{-4}$ s^{-1}, and $k_L{}^{CH_4} = 0$, all ligands.

Table II. Fits Values from Equation 15 for Methane Formation from $CH_3Co(D_2H_2)HOH$ Plus Various Ligands, 50.0 °C, 1.0 N KOH

ligand	$K_f{}^{app}$, M^{-1}	$k_L{}^{CH_4}$, s^{-1}
pyridine	75.5 ± 3.3	$2.01 \pm 2.82 \times 10^{-6}$
dimethoxyethylamine	144 ± 5	$-6.06 \pm 22.4 \times 10^{-7}$
S-methylmercaptoethanol	6.06 ± 0.21	$8.84 \pm 25.9 \times 10^{-7}$
2-mercaptoethanol	3500 ± 50	$7.15 \pm 7.96 \times 10^{-7}$

$$k_{obsd}{}^{CH_4} = (k_{aquo}{}^{CH_4} + k_L{}^{CH_4} K_f{}^{app} [L]_f)/(1 + K_f{}^{app} [L]_f) \quad (15)$$

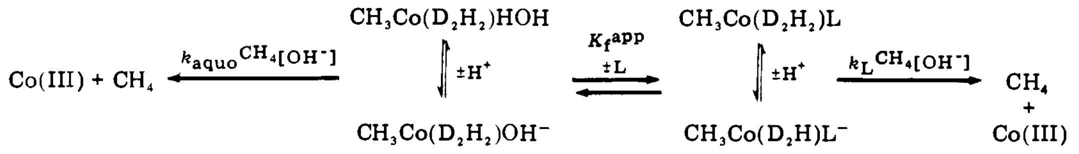
where

$$K_f{}^{app} = ([CH_3Co(D_2H_2)L] + [CH_3Co(D_2H)L^-])/([CH_3Co(D_2H_2)HOH] + [CH_3Co(D_2H_2)OH^-])[L]_f \quad (16)$$

$$[L]_f = [L]_T - [CH_3Co(D_2H_2)L] - [CH_3Co(D_2H)L^-] \quad (17)$$

and $[L]_f$ and $[L]_T$ are the equilibrium and total ligand concentrations, respectively. Using $k_{aquo}{}^{CH_4} = 1.28 \times 10^{-4}$ s^{-1} in 1.0 N KOH (from k_{obsd} and yield for CH_4 formation, Table I) these data were fit by a nonlinear least-squares method to eq 15 to provide the apparent rate and equilibrium constants listed in Table II. In all cases the apparent first-order rate constant for methane formation from the N- and S-liganded methylcobaloxime species was statistically indistinguishable from zero, although ligand affinity for the cobalt center varied by some 580-fold. In fact, the solid lines in Figure 3 have been calculated from these results and eq 15 using $k_L{}^{CH_4} = 0$ for all ligands. The unifying aspect of the apparent lack of reactivity of the N- and S-liganded species is shown graphically in Figure

Scheme II



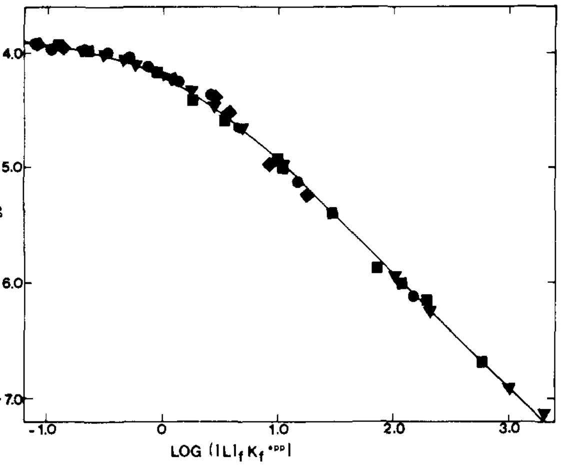
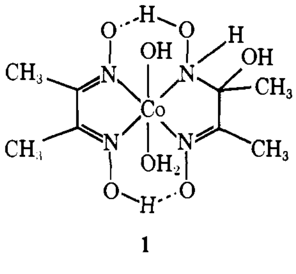


Figure 4. Plot of log $k_{obsd}^{CH_4}$ for methane formation from methylcobaloximes at 50.0 °C, 1.0 N KOH vs. log ($[L]_f K_f^{app}$) for the ligands SMME (♦), py (●), DEA (■), and 2-ME (▼). The *solid line* was calculated from eq 15 using $k_{aquo}^{CH_4} = 1.28 \times 10^{-4}$ s^{-1} and $k_L^{CH_4} = 0$.

4, in which all the data for all ligands (plotted as log $k_{obsd}^{CH_4}$ vs. log ($[L]_f K_f^{app}$)) are seen to fit a single line calculated from eq 15 assuming $k_L^{CH_4} = 0$. Assuming that a 10% deviation of $k_{obsd}^{CH_4}$ from the calculated line at the highest values of $[L]_f K_f^{app}$ is the limit of detectability, all the N- and S-liganded species must be at least four orders of magnitude less reactive than the hydroxo species in 1.0 N KOH.

Cobalt-Containing Products. Cobalt-containing products were obtained from alkaline aqueous reaction mixtures after neutralization, lyophilization, and continuous extraction with chloroform. Purification of the extract by silica gel chromatography produced an orange fraction eluting with acetone which was in all respects identical with unaltered starting material, $CH_3Co(D_2H_2)HOH$, in an overall yield of 19%. Further elution of the silica gel column with methanol and water produced a brown fraction (overall yield 67%) which, after recrystallization from methylene chloride–cyclohexane, gave the ^1H NMR spectrum shown in Figure 5A (in D_2O, external Me_4Si reference). The spectrum shows a ragged multiplet ca. 1.9–2.8 ppm downfield from external Me_4Si indicating diastereotopic equatorial methyl groups, a sharp singlet at ca. 1.5 ppm (ca. one proton relative to 12 protons in the multiplet), and a broad, one-proton resonance centered at 0.8 ppm. After 24 h, the spectrum of Figure 5B was obtained which shows that the one-proton resonance at 1.5 ppm had completely exchanged with solvent deuterons. The broad signal at 0.8 ppm is also exchangeable, although on a much longer time scale. It was about 50% exchanged after 5 days at room temperature. This compound was converted in good yield to the dichlorocobaloxime acid, $H[Co(D_2H_2)Cl_2]$, by stirring overnight in 20% aqueous HCl. The ^1H NMR spectrum of the $H[Co(D_2H_2)Cl_2]$ thus obtained is shown in Figure 5C and is identical with that of an authentic sample of this material. Based on these observations, the structure of this demethylated cobalt-containing product is assigned to that of compound **1**, an aquohydroxocobaloxime analogue in which one Schiff's base linkage has become hydrated. Satisfactory elemental analysis for this formulation (Co, C, H, N, O) was obtained (see Experimental Section). Since carbinolamine dehydration is well known to be acid catalyzed[35] the conversion of **1** to a bis(dimethylglyoximato) chelate in aqueous acid is consistent with this formulation. Also consistent is the observation of diastereotopic equatorial methyl groups and exchangeable one-proton singlets which can be tentatively assigned as -OH at 1.5 ppm and NH at 0.8 ppm based on line shapes and relative exchange rates. From these observations it is concluded that base-induced carbon–cobalt bond cleavage in methylcobaloxime leads to formation of **1**, or a material converted to **1** upon neutralization, and a base-stable methylcobalt side product which is rapidly converted to $CH_3Co(D_2H_2)HOH$ upon neutralization.



1

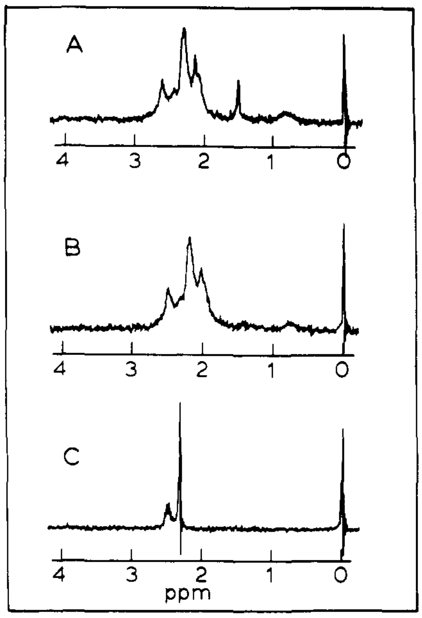
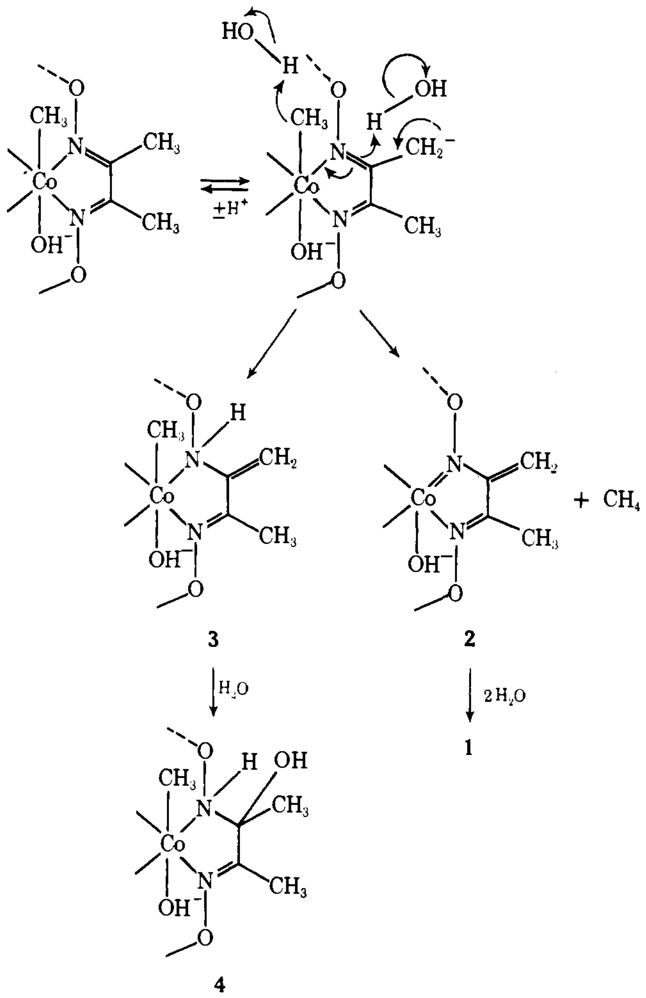


Figure 5. (A) ^1H NMR spectrum of compound **1** in D_2O, external Me_4Si reference shown. (B) ^1H NMR spectrum of this sample (part A) 24 h after preparation. (C) ^1H NMR spectrum of the product obtained from compound **1** after stirring overnight in 20% aqueous HCl, in Me_2SO-d_6 (internal Me_4Si).

Many attempts were made to obtain the methylcobalt side product directly from the alkaline reaction mixtures without success. Direct, prolonged liquid–liquid extraction of aqueous alkaline reaction mixtures (for as long as 6 weeks) with various solvents failed to produce sufficient amounts of material for workup and characterization. However, lyophilization of alkaline aqueous reaction mixtures followed by continuous extraction of the lyophilizate with chloroform did provide a photolabile material which had slightly different chromatographic characteristics than starting material, but all attempts to purify the material led to its reversion to $CH_3Co(D_2H_2)HOH$.

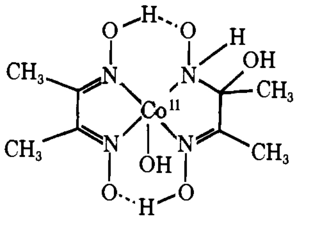
Mechanism. Several mechanisms can be envisioned which are generally consistent with the above observations, although none of these seem to satisfactorily explain all of the results. Cartaño and Ingraham[25] have shown that the equatorial methyl groups of $CH_3Co(D_2H_2)HOH$ are acidic and undergo exchange with solvent deuterons in alkaline Me_2SO-d_6–D_2O mixtures at 35 °C at a rate that is twice as fast as methane formation at 50 °C. We have recently confirmed this exchange[36] and its kinetic competence[37] for methane formation in several solvents both for $CH_3Co(D_2H_2)HOH$ and $CH_3Co(D_2H_2)py$. These results suggest the possibility of Mechanism I in which prior dissociation of a proton from an equatorial methyl group activates the complex for expulsion

Mechanism I



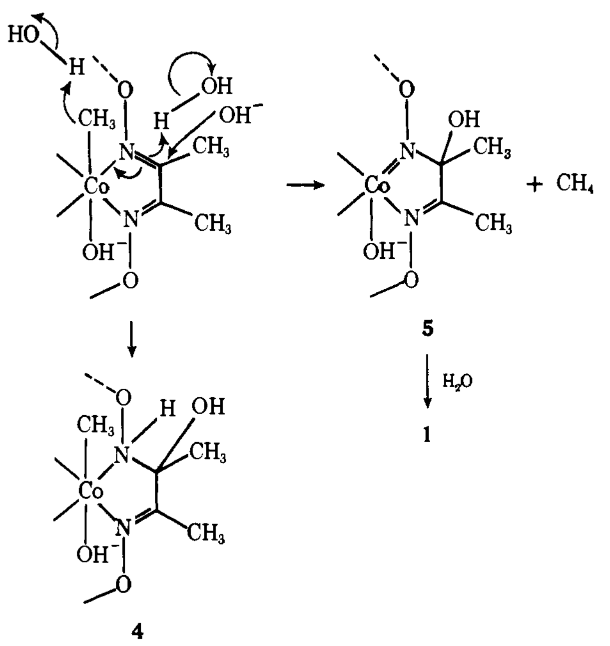
of a methyl carbanion to form the dealkylated intermediate (**2** which hydrates to **1**) or formation of the side product (**3**) which would be expected to become hydrated in alkaline solution to form **4**.

An alternative, but similar mechanism which involves direct attack of hydroxide ion on the equatorial ligand system leads to the same products (Mechanism II). In either case, compound **4**, the methyl analogue of **1**, is the expected side product. In this regard, it is interesting to note that Simândi and coworkers[38] found that aquocobaloxime(II) reacts with hydroxide ion in aqueous base to form an acid-labile compound assigned the structure **6**, which is the cobalt(II) analogue of **1** and **4**. While at first glance the apparently rapid dehydration of **4** upon neutralization of alkaline aqueous reaction mixtures may seem inconsistent with the fact that conversion of **1** to $H[Co(D_2H_2)Cl_2]$ appears to require much more strongly acidic conditions, this is completely in accord with known differences in reactivity of cobalt(III) cobaloximes with inorganic axial ligands and organocobaloximes.[39] Simândi reports that **6** is rapidly converted to aquocobaloxime(II) upon neutralization.[38,43]



6

Mechanism II



While the apparent lack of reactivity of $CH_3Co(P_2H_2)HOH$ would seem to favor Mechanism I, it is not inconsistent with Mechanism II, assuming that a large electronic effect by the glyoxime substituent would be possible. Unfortunately, neither of these mechanisms seems to provide an adequate explanation of the extremely low reactivity of all species other than methyl(hydroxo)cobaloxime. A mechanism can be envisioned to explain this effect by assuming that base-assisted internal nucleophilic attack of the axial hydroxo ligand on the equatorial ligand system is required for methane formation. However, this mechanism seems contrived and it seems unlikely that the aquo complex would not undergo similar reaction and that Mechanism II (i.e., external nucleophilic attack by OH^-), which should come into play at sufficiently high concentrations of ligand, would be so much slower. A better understanding of this phenomenon will have to await further experimentation, which is in progress.

It should, finally, be pointed out that a base-catalyzed homolytic carbon-cobalt bond dissociation mechanism in which a methyl radical abstracts a hydrogen (or deuterium) from an equatorial methyl group cannot be ruled out with the present data, since equatorial methyl proton exchange is evidently faster than methane formation under these conditions.[3,25]

Acknowledgment. The author is grateful to the Department of Chemistry of The University of Texas at Dallas for the use of the Finnigan 3200 GC/MS and to Dr. Richard A. Caldwell for his assistance with this instrument.

References and Notes

(1) This project was supported by the National Institutes of Health, U.S. Public Health Service Grant GM23215, and the donors of the Petroleum Research Fund, administered by the American Chemical Society.

(2) Abbreviations: $CH_3Co(D_2H_2)L$ = methyl(ligand)bis(dimethylglyoximato)cobalt(III) = methyl(ligand)cobaloxime; $CD_3Co(D_2H_2)HOH$ = trideuteriomethyl(aquo)cobaloxime; $CH_3Co(P_2H_2)L$ = methyl(ligand)bis(diphenylglyoximato)cobalt(III); $CH_3Co(D_2B_2F_4)HOH$ = boron difluoride bridged derivative of methyl(aquo)cobaloxime (chelate **2** in ref 4); py = pyridine; DEA = dimethoxyethylamine (aminoacetaldehyde dimethyl acetal); SMME = *S*-methyl-2-mercaptoethanol; 2-ME = 2-mercaptoethanol.

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Synthesis, Catalytic Activity, and Behavior of Phase-Transfer Catalysts Supported on Silica Gel. Strong Influence of Substrate Adsorption on the Polar Polymeric Matrix on the Efficiency of the Immobilized Phosphonium Salts[1]

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Abstract: Phase-transfer (PT) catalysts, namely, phosphonium salts, have been immobilized on silica gel; good organofunctionalization has been obtained ranging from 1.0 to 0.7 mequiv $[PR_4]^+/g$. The synthesis of phosphonium salt functionalized silica gels **1–4**, with different spacer chain lengths between the polymeric matrix and the catalytic center (from 3 to 27 atoms), is reported. Ketone adsorption constants (K_{ads}) on nonfunctionalized and functionalized silica gel, and their comparison with pseudo-first-order rate constants (k_{obsd}) in the aqueous sodium borohydride reduction of ketones under PTC conditions, show that adsorption phenomena are the main factors determining the reaction rate; moreover, C,O-alkylation experiments show that the catalyzed reaction takes place in a very polar environment formed by the functionalized silica gel and the water adsorbed on it. These immobilized catalysts can be reused several times with a little loss of activity, but they are hydrolyzed at high pH values.

Phase-transfer (PT) catalysts, such as the classic onium salts[2,3] or more complex systems, such as crown ethers and cryptands,[3] have been immobilized on insoluble polystyrene matrices with various degrees of cross-linking. Their activity remains reasonably high if the catalytic center is sufficiently far from the polymer backbone (alkyl chain interposed),[4] or if the resin is very porous.[5] This arrangement has certain advantages over the use of free catalyst: the reaction is clean and its products are not contaminated by the catalyst.

However, all the literature reported data seem to show that

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