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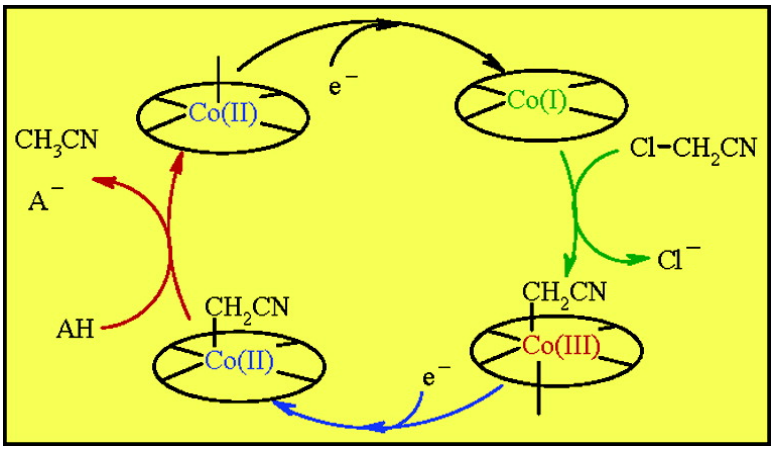

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Role of Protonation and of Axial Ligands in the Reductive Dechlorination of Alkyl Chlorides by Vitamin B_{12} Complexes. Reductive Cleavage of Chloroacetonitrile by Co(I) Cobalamins and Cobinamides

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Abstract: Cobalt(I) cobalamin and cobinamide are efficient catalysts of the hydrogenolysis of aliphatic chloro compounds. Taking chloroacetonitrile as example, the first requirement for high catalytic efficiency is fulfilled by the high reactivity of the Co(I) complex toward the substrate, leading to the alkylcobalt(III) complex. This is further reduced into the alkylcobalt(II) complex. However, the fact that these two reactions are fast is not enough to ensure an efficient catalysis: in DMF catalysis is very poor, while it is high in water. The experiments carried out in DMF with addition of an acid show that a crucial step in the catalytic process is the proton transfer decomposition of the alkylcobalt(II) complex, leading to the product, and closing the catalytic loop by regeneration of the cobalt(I) complex. Another important feature of these catalytic reactions is the role played by axial ligands present in the solution, particularly those that are produced by the catalytic reaction itself, namely, chloride ions and the counteranion of the added acid. The stronger these ligands, the more negative the potential required for the reduction of the alkylcobalt(III) complex. This amounts to a self-moderation effect: the more efficient catalysis, the slower its second step, i.e., the conversion of the alkylcobalt(III) complex into the alkylcobalt(II).

Introduction

Common chlorinated solvents, such as polychloroethenes, polychloroethanes, and polychloromethanes, form one of the main groups of environmental pollutants present in the soil and groundwater of many industrial sites. This contamination is particularly dangerous in view of their toxicity or carcinogenic character.[2] Degradation mechanisms and the nature of the ensuing products in various environmental configurations have been actively investigated.[3] It was shown that although these pollutants undergo biotransformations, these are slow and may lead to secondary stable pollutants. These difficulties have aroused interest for several abiotic approaches. Among them reduction by metals, typically iron,[4] palladium deposited on iron or graphite,[5] and other reducing agents such as pyrite and magnetite,[6] has been mostly developed, without leading, however, to fully satisfying results, because of deactivation of the reducing material. Direct electrochemical reduction is another approach that has been developed in ex situ conditions, involving, for example, carbon[7] or nickel electrodes.[8] But detailed investigations of electrochemical reductive mechanisms reveal that those pollutants are difficult to reduce in an outer-sphere electron-transfer manner.[9] Another approach thus consists of taking advantage of the implication of low-valent cobalamin and other cobalt corrinoids in the enzymatic reduction of a large variety of organic halides in many anaerobic bacteria[10] and the possible implication of organocobalt intermediates[11] to overcome this problem. The implication of cobalt corrinoids as cofactors in several isolated reductive dehalogenation enzymes has indeed been demonstrated.[12−14]

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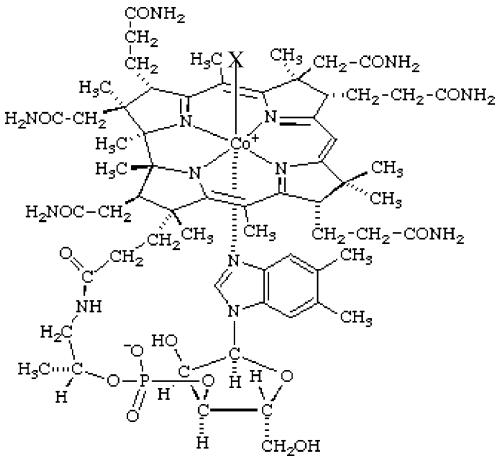
(2) Toxicology and Carcinogenesis Studies of Tetrachloroethylene; NTP Technical Report No. 311; National Toxicology Program: Research Triangle Park, NC, 1986.
(3) (a) Fetzner, S. *Appl. Microbiol. Biotechnol.* **1998**, *50*, 633. (b) Lendvay, J. M.; Loeffler, F. E.; Dollhopf, M.; Aiello, M. R.; Daniels, G.; Fathepure, B. Z.; Gebhard, M.; Heine, R.; Helton, R.; Shi, J.; Krajmalnik-Brown, R.; Major, C. L., Jr.; Barcelona, M. J.; Petrovskis, E.; Hickey, R.; Tiedje, J. M.; Adriaens, P. *Environ. Sci. Technol.* **2003**, *37*, 1422. (c) Hohnstock-Ashe, A. M.; Plummer, S. M.; Yager, R. M.; Baveye, P.; Madsen, E. L. *Environ. Sci. Technol.* **2001**, *35*, 4449.
(4) (a) Li, T.; Farrell, J. *Environ. Sci. Technol.* **2000**, *34*, 173. (b) Scherer, M. M.; Balko, B. A.; Gallagher, D. A.; Tratnyek, P. G. *Environ. Sci. Technol.* **1998**, *32*, 3026.
(5) (a) Lien, H.-L.; Zhang, W.-X. *Colloids Surf. A: Physicochem. Eng. Aspects* **2001**, *191*, 97. (b) Prati, L.; Rossi, M. *Appl. Catal. B: Environ.* **1999**, *23*, 135. (c) Muftikian, R.; Nebesky, K.; Fernando, Q.; Korte, N. *Environ. Sci. Technol.* **1996**, *30*, 3593. (d) Lowry, G. V.; Reinhard, M. *Environ. Sci. Technol.* **2001**, *35*, 696.
(6) Lee, W.; Batchelor, B. *Environ. Sci. Technol.* **2002**, *36*, 5147.
(7) Nagaoka, T.; Yamashita, J.; Kaneda, M.; Oguar, K. *J. Electroanal. Chem.* **1992**, *335*, 187.
(8) Liu, Z.; Betterton, E. A.; Arnold, R. G. *Environ. Sci. Technol.* **2000**, *34*, 804.
(9) Costentin, C.; Savéant, J.-M.; Robert, M. *J. Am. Chem. Soc.* **2003**, *125*, 10729.
(10) Hollinger, C.; Wohlfarth, G.; Diekert, G. *FEMS Microbiol. Rev.* **1999**, *22*, 383.
(11) (a) Pratt, J. M. *Inorganic Chemistry of Vitamin B12*; Academic Press: New York, 1972. (b) *Chemistry and Biochemistry of B12*; Banerjee, R., Ed., Wiley: New York, 1999.

Chart 1



In this connection, vitamin B_{12} (Chart 1) has been employed as a biomimetic model for the enzymatic reduction of polychloroethenes, and it seems to be a promising catalyst for the dechlorination of halogenated pollutants.[15] Despite the availability of a wide body of data concerning the redox chemistry of cobalt corrinoids,[16] the reduction mechanisms are unclear. On the basis of the nonappearance of a trichlorovinyl−cobalamin complex under spectroscopic monitoring, an outer-sphere electron-transfer mechanism was first proposed for the reaction between Cob(I)alamin and tetrachloroethylene, leading to the corresponding vinyl radical, which can be further reduced to trichloroethylene.[17] However, studies of chlorovinylcobalamin and vinylcobalamin indicated that the reduction potential for trichlorovinylcobalamin is probably close to the Co(I)/Co(II) couple of B_{12}, which explains why trichlorovinylcobalamin could never been detected.[18] The reductive dechlorination of trichloroethylene is likely to involve chlorinated vinylcobalamins, as indicated by mass spectrometry detection of di and monochloro vinylcobalamins.[19] Experiments using chlorovinylcobaloxime complexes show that they are reduced by Co(I),[20] but the mechanism of their formation remains unclear. A vinylic nucleophilic substitution or the combination of chlorinated vinyl radical with Co(II) have been suggested.[21]

Among alkyl halides, vicinal dibromides react with Co(I) porphyrins to give alkenes according to a positive halogen abstraction mechanism, thus giving rise to an efficient catalyzed electrochemical debromination of these substrates.[22]

Monohaloalkanes react with Co(I)balamin in *N*,*N*-dimethylformamide (DMF), to form an alkyl−Co(III) complex.[23] As shown with *n*-butyl bromide as the substrate, this may be further reduced to the alkyl−Co(II) complex, which cleaves, leading to a catalytic process.[24] Catalysis is however very sluggish. Other studies have been performed on the reductive cleavage mechanism of alkyl−cobalt complexes,[25] with particular emphasis of the dependence of the redox characteristics of the alkyl complex upon the nature of the axial alkyl ligand.[26]

The reason for the lack of efficient catalysis in these cases is unknown. This was the first task of the work reported below, which aims at designing a mechanism by which the alkyl−cobalt complex may be decomposed so as to obtain the reductive cleavage products and to regenerate the cobalt(I) complex and thus to foster catalysis. The reductive cleavage of chloroacetonitrile is taken as example. Both cobalamins and cobinamides have been used as catalyst. After showing that efficient catalysis is obtained when water or a water−alcohol mixture is used as the solvent, the reaction will be investigated in a nonprotic media with progressive addition of an acid to unravel the mechanism that leads to an efficient catalysis. One of the key intermediate of the catalytic process is the alkyl−cobalt(III) complex, which may be diversely liganded in the second axial position by the various ligands present in the medium in the case of cobinamide and cobalamin and also by the benzimidazole attached to the corrin ring in the latter case. Besides making the mechanistic analysis more complex, the interference of several forms of the alkyl−cobalt(III) complex offers an opportunity to uncover a relationship between the catalytic efficiency and the nature of this second axial ligand.

Results and Discussion

Reaction in a Protic Medium. A series of cyclic voltammetric experiments were carried out in 70/30 water−ethanol mixtures on a glassy carbon working electrode, the addition of ethanol helping solubilize chloroacetonitrile.

In the absence of chloroacetonitrile, Co(III) cobinamide exhibits two cyclic voltammetric waves. The second of these, shown in Figure 1, is reversible and corresponds to formation of the Co(I) as results from comparison with the Co(II) base-off reduction wave of vitamin B_{12}[16] (Scheme 1). As represented in the scheme, the most stable forms involve two axial ligands for Co(III), one for Co(II), and no axial ligand for Co(I).[11,16]

The direct reduction of chloroacetonitrile at the same carbon electrode in the same medium occurs beyond the discharge of the solvent-supporting electrolyte system. Addition of chloroacetonitrile to the cobinamide solution results in the appearance of a strong catalytic current response. It appears between the cobinamide Co(II)/Co(I) wave (where the Co(I) complex is generated) and the direct reduction wave of chloroacetonitrile.[27] It consists of two close-spaced irreversible waves, corresponding

(12) (a) Neumann, A.; Wohlfarth, G.; Diekert, G. *Arch. Microbiol.* **1995**, *163*, 276. (b) Neumann, A.; Wohlfarth, G.; Diekert, G. *J. Biol. Chem.* **1996**, *271*, 16515.
(13) Magnuson, J. K.; Stern, R. V.; Gossett, J. M.; Zinder, S. H.; Burris, D. R. *Appl. Environ. Microbiol.* **1998**, *64*, 1270.
(14) Kräutler, B.; Fieber, W.; Ostermann, S.; Fasching, M.; Ongania, K.-H.; Gruber, K.; Kratky, C.; Mikl, C.; Siebert, A.; Diekert, G. *Helv. Chim. Acta* **2003**, *86*, 3698.
(15) (a) Sorel, D.; Lesage, S.; Brown, S.; Millar, K. *Ground water Monit. Rem.* **2001**, *21*, 140. (b) Ruppe, S.; Neumann, A.; Diekert, G.; Vetter, W. *Environ. Sci. Technol.* **2004**, *38*, 3063.
(16) Lexa, D.; Savéant, J.-M. *Acc. Chem. Res.* **1983**, *16*, 235.
(17) Shey, J.; van der Donk, W. A. *J. Am. Chem. Soc.* **2000**, *122*, 12403.
(18) McCauley, K. M.; Wilson, S. R.; van der Donk, W. A. *J. Am. Chem. Soc.* **2003**, *125*, 4410.
(19) Lesage, S.; Brown, S.; Millar, K. *Environ. Sci. Technol.* **1998**, *32*, 2264.
(20) (a) McCauley, K. M.; Wilson, S. R.; van der Donk, W. A. *Inorg. Chem.* **2002**, *41*, 393. (b) Rich, A. E.; DeGreeff, A. D.; McNeill, K. *Chem. Commun.* **2002**, 234.
(21) McCauley, K. M.; Wilson, S. R.; van der Donk, W. A. *Inorg. Chem.* **2002**, *41*, 5844.
(22) (a) Lexa, D.; Savéant, J.-M.; Schäfer, H. J.; Su, K. B.; Vering, D. L.; Wang, J. *J. Am. Chem. Soc.* **1990**, *112*, 6162. (b) Connors, T. F.; Arena, J.; Rusling, J. F. *J. Phys. Chem.* **1988**, *92*, 2810 (c) Rusling, J. F.; Connors, T. F.; Owlia, A. *Anal. Chem.* **1987**, *59*, 2123. (d) Owlia, A.; Wang, Z.; Rusling, J. F. *J. Am. Chem. Soc.* **1989**, *111*, 5091. (e) Zhou, D.-L.; Gao, J.; Rusling, J. F. *J. Am. Chem. Soc.* **1995**, *117*, 1127. (f) Davies, T., J.; Garner, A. C.; Davies, S., G.; Compton, R. G. J. *Electroanal. Chem.* **2004**, *570*, 171.
(23) (a) Schrauzer, G. N.; Deutsch, E.; Windgassen, R. J. *J. Am. Chem. Soc.* **1968**, *90*, 2441. (b) Schrauzer, G. N.; Deutsch, E. *J. Am. Chem. Soc.* **1969**, *91*, 3341.
(24) Lexa, D.; Savéant, J.-M.; Soufflet, J. P. *J. Electroanal. Chem.* 1979, *100*, 159.
(25) (a) Lexa, D.; Savéant, J.-M. *J. Am. Chem. Soc.* **1978**, *100*, 3220. (b) Kim, M.-H.; Birke, R. L. *J. Electroanal. Chem.* **1983**, *144*, 331.
(26) Zhou, D.-L.; Tinembart, O.; Scheffold, R.; Walder, L. *Helv. Chim. Acta* **1990**, *73*, 2225.

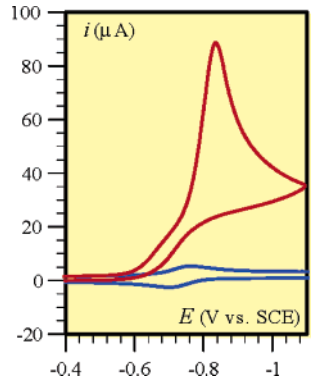
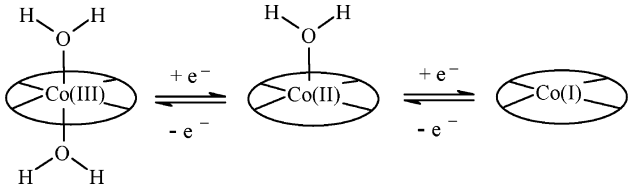
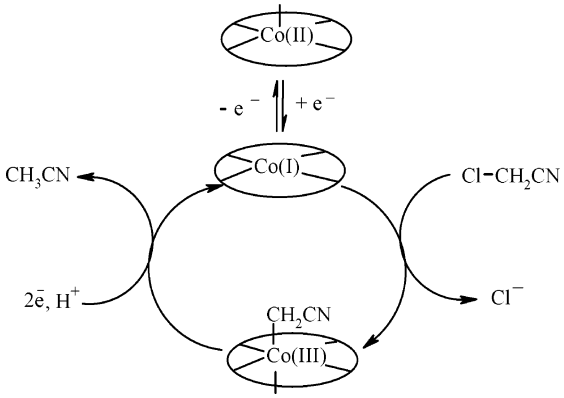


Figure 1. Cyclic voltammetry of cobinamide 0.5 mM alone (blue) and in the presence of 1.5 mM chloroacetonitrile (red) in a 70/30 H_2O−EtOH + 0.1 M NaCl mixture on a glassy carbon electrode at a scan rate of 0.2 V/s.

Scheme 1



Scheme 2



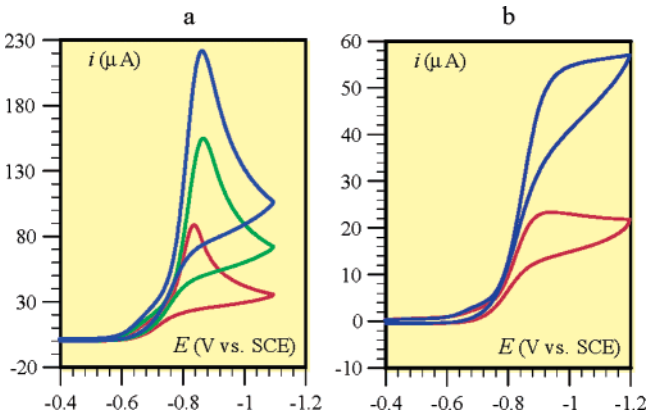


Figure 2. Catalysis of the reduction of chloroacetonitrile by the cobinamide Co(II)/Co(I) couple in a 70/30 H_2O−EtOH + 0.1 M NaCl mixture on a glassy carbon electrode at a scan rate of 0.2 V/s. (a) [cobinamide] = 0.5 mM, [$ClCH_2CN$] = 1.5 mM (red), 3.1 mM (green), 4.6 mM (blue); (b) [cobinamide] = 0.02 mM, [$ClCH_2CN$] = 1.5 mM (red), 4.6 mM (blue).

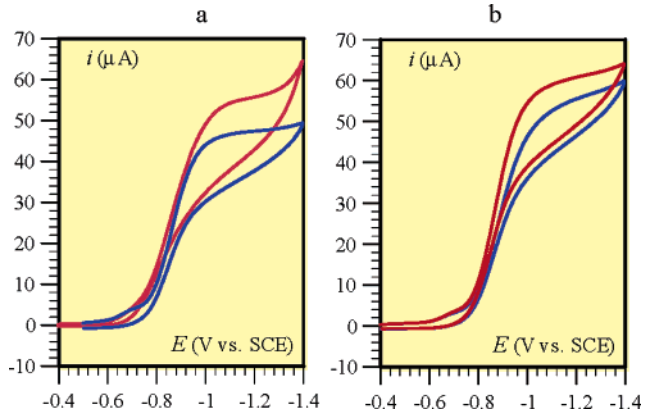


Figure 3. Catalysis of the reduction of chloroacetonitrile by the cobinamide Co(II)/Co(I) couple in 70/30 H_2O−EtOH buffered media on a glassy carbon electrode at a scan rate of 0.2 V/s (a) as a function of pH, pH = 2.6 (red) and 7.4 (blue), and (b) as a function of buffer concentration at pH = 7.4, 0.01 M (blue) and 0.1 M (red). [cobinamide] = 0.02 mM, [$ClCH_2CN$] = 4.6 mM.

respectively to the formation and reduction of a new complex resulting from the reaction of the Co(I) cobinamide with chloroacetonitrile. These observations suggest the mechanism represented in Scheme 2, where the alkyl−Co(III) complex formed at the Co(II)/Co(I) wave is further reduced at the level of the second wave. A strong catalysis takes place at this second wave, implying that the Co(I) is regenerated through a further electron transfer step, presumably with the help of proton donors present, together with the formation of acetonitrile. For simplicity, the axial ligand other than the cyanomethyl group has been omitted. The question of the nature and influence of axial ligands on the catalytic process will be discussed in detail afterward.

The height of the catalytic wave and its peak shape indicate that the catalytic reaction is so fast that the current is governed, at least partially, by the diffusion of the substrate, chloroacetonitrile, toward the electrode surface.[28] Figure 2 gathers various experiments aiming at a more complete characterization of the catalytic process. As seen in Figure 2a, the catalytic current remains controlled by substrate diffusion, at least partially, when increasing the substrate concentration, provided the excess factor, the ratio of the substrate to catalyst concentration, stays below 10. For larger values of the excess factor, obtained with a much smaller catalyst concentration, the catalytic response tends to take the classical plateau shape.[28] A rough estimate of the overall catalytic rate constant leads to 3×10^6 M^{-1} s^{-1}.[29]

Scheme 2 requires that a proton should be consumed in order to close the catalytic loop. Attempts to see whether this step can be identified by means of its contribution to the overall kinetics are summarized in Figure 3.

There is a definite, but very small, increase of catalysis in buffered medium upon decreasing the pH, or, at a given pH, upon increasing buffer concentration. These observations point to an involvement of a protonation step in the reaction mechanism, but the effect is so marginal that further examination of the problem seems indispensable. Similar conclusions were drawn from a parallel study of catalysis of the same substrate

(27) The noncatalytic reduction potential of chloroacetonitrile cannot be characterized in the experimental medium (70−30 H_2O/EtOH) since the reduction occurs close to the solvent wall.

(28) Savéant, J.-M.; Su, K. B. *J. Electroanal. Chem.* **1984**, *171*, 341.

(29) The overall catalytic rate constant (3×10^6 M^{-1} s^{-1}) was determined from the plateau current obtained in the catalytic response with large excess factor: $i_p = FSc_P^0\sqrt{D}\sqrt{kc_S^0}$, where S is the electrode surface (0.07 cm^2), c_P^0 the catalyst concentration, c_S^0 the substrate concentration, and D the diffusion constant (10^{-5} cm^2/s).

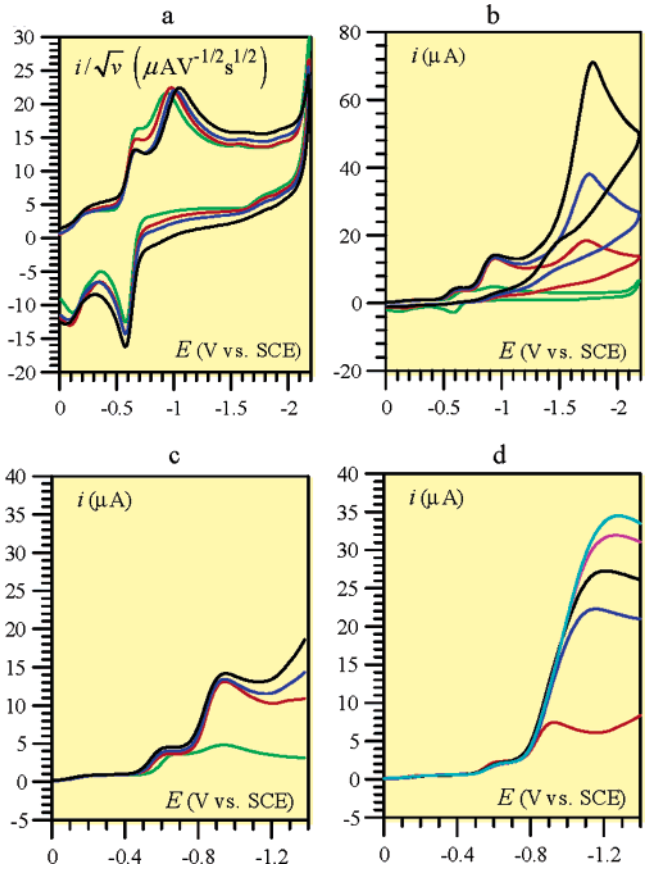


Figure 4. Catalysis of the reduction of chloroacetonitrile by the cobinamide Co(II)/Co(I) couple in DMF + 0.1 M NBu_4ClO_4. (a) cobinamide (1 mM) alone as a function of the scan rate $v = 0.05$ V/s (green), 0.1 V/s (red), 0.2 V/s (blue), 0.5 V/s (black). (b) Cobinamide (1 mM) in the presence of varying $ClCH_2CN$ concentration: 0 mM (green), 1 mM (red), 2.5 mM (blue), 5 mM (black) at 0.05 V/s. (c) Same as part b, limiting the potential excursion to avoid the direct reduction of $ClCH_2CN$ and ignoring the anodic traces. (d) Cobinamide (0.5 mM) in the presence of 2 mM $ClCH_2CN$ and varying acetic acid concentration: 0 mM (red), 1 mM (blue), 2.5 mM (black), 5 mM (magenta), 10 mM (cyan) at 0.05 V/s.

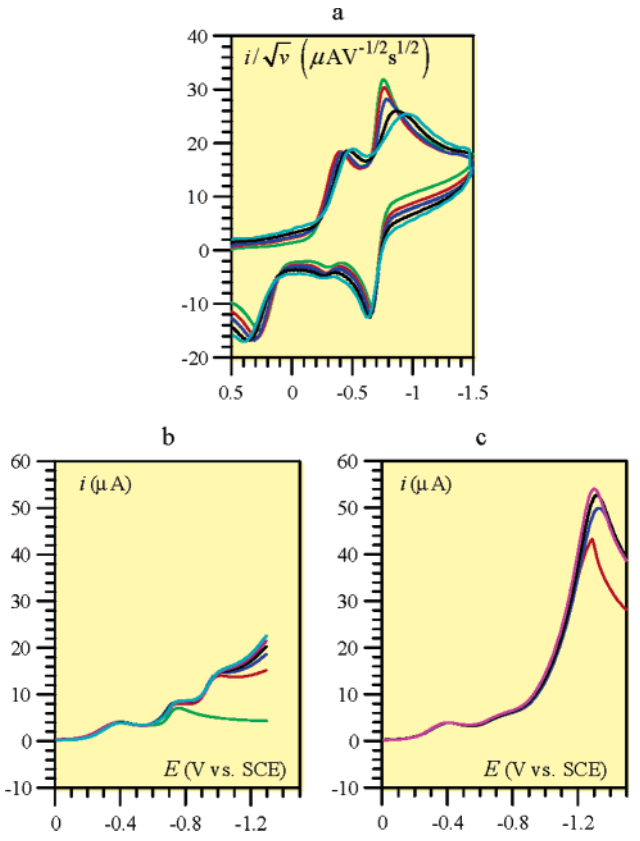


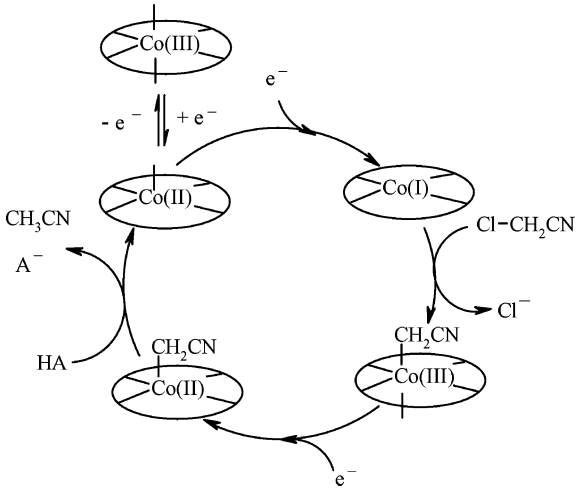
Figure 5. Catalysis of the reduction of chloroacetonitrile by the cobalamin Co(II)/Co(I) couple in DMF + 0.1 M NBu_4ClO_4. (a) Cobalamin (1 mM) alone as a function of the scan rate $v = 0.05$ V/s (green), 0.1 V/s (red), 0.2 V/s (blue), 0.5 V/s (black), 1 V/s (cyan). (b) Cobalamin (1 mM) in the presence of varying $ClCH_2CN$ concentration: 0 mM (green), 2 mM (red), 4 mM (blue), 6 mM (black), 8 mM (magenta), 10 mM (cyan) at 0.05 V/s. (c) Cobalamine (0.5 mM) in the presence of 2 mM $ClCH_2CN$ and varying acetic acid concentration: 1 mM (red), 5 mM (blue), 10 mM (black), 15 mM (magenta), at 0.05 V/s.

by cobalamin. It thus appears that protonation by water is sufficiently rapid to make steps precedent the protonation step, such as the formation of the alkyl complex, rate determining, or close to being so. This is the reason that we undertook an investigation of the catalytic properties of the same complexes in a nonprotic solvent, namely DMF. We thus expect, as concerns the protonation step, to start from an unfavorable situation and to evidence its interference upon adding an acid to the medium.

Reaction in DMF. Effect of Proton Addition. The results of an investigation of the catalytic responses obtained in this solvent with the cobinamide and cobalamin complexes are summarized in Figures 4 and 5, respectively. In the absence of substrate, two wave systems appear, corresponding first to the Co(III)/Co(II) reduction and then to the Co(II)/Co(I) reduction. The Co(III)/Co(II) system is quasireversible because of the interference of various forms of the Co(III) complex involving chloride ion and O- and N-ligation by DMF molecules with cobinamide and by the attached benzimidazole ligand in the case of cobalamin. The Co(II)/Co(I) couple, which is the couple of interest in the catalytic process, shows a simpler response. It is reversible, at least at the lowest end of the scan rate range (Figures 4a and 5a). Upon addition of chloroacetonitrile, the Co(II)/Co(I) wave becomes irreversible and increases in height as expected from the formation of the $Co(III)CH_2CN$ complex (Figure 4b,c). We note that the reduction wave of this complex is practically merged with the wave where the complex is formed in the case of cobinamide, whereas, with cobalamin, the $Co(III)CH_2CN/Co(II)CH_2CN$ wave appears at a potential clearly more negative than the peak potential of the Co(I)/Co(III)CH_2CN wave (Figure 5b). In both cases, catalysis, if any, is very weak. It is remarkable in this connection that the current increase is practically independent of the amount of $ClCH_2CN$ added. These observations point to the conclusion that the formation of the $Co(III)CH_2CN$ complex is fast but that the decomposition of the $Co(II)CH_2CN$ complex formed upon reduction of the former is slow, thus hampering the closing of the catalytic loop. In this respect the difference in behavior with the protic medium depicted in the preceding section is striking. The uncatalyzed reduction of chloroacetonitrile appears at more negative potential, as can be seen in Figure 4b.

Addition of an acid (acetic acid was selected in this purpose) triggers a quite significant increase of the $Co(III)CH_2CN/Co(II)CH_2CN$ response (Figures 4d and 5c). Protonation-triggered deligation of $-CH_2CN$ thus appears as an essential step in the completion of the catalytic loop, pointing to the catalysis mechanism depicted in Scheme 3. This is valid in an aprotic solvent with addition of an acid HA (here CH_3CO_2H), as well

Scheme 3



as in a protic media, as in water, in which case the solvent itself plays the role of HA.

Role of Axial Ligands. In Scheme 3, we have again ignored, for simplicity, the role of axial ligation. Deciphering the complex ligation/deligation effects on the shape and potential location of the Co(III)/Co(II) wave system would indeed seem of little interest for the comprehension of the catalytic process, since catalysis is triggered by the reduction of Co(II) into Co(I). However, ligation of Co(III) in the alkyl complex may well influence the course of catalysis, since the reduction of Co(III)CH_2CN to Co(II)CH_2CN is part of the catalytic loop and may depend on the nature of the ligand that occupies the other axial position besides the alkyl ligand. An indication of that such effects are operating is the observation that the location of the catalytic wave depends on the amount of acid added to improve catalysis, as can be seen in Figures 4d and 5c. Another indication is provided by the variation of the reduction wave of the Co(III)CH_2CN complex with the scan rate before the addition of acid, as can be seen in Figure 6 in the case of chlorocobalamin. The scan starts after the Co(III)/Co(II) wave to examine more conveniently both the formation of the Co(III)CH_2CN complex at the Co(II)/Co(I) wave and its successive reduction at more negative potentials. The addition of chloroacetonitrile has rendered the Co(II)/Co(I) wave irreversible, and a second wave appears that correspond to the reduction of the Co(III)CH_2CN complex to give the Co(II)CH_2CN complex,

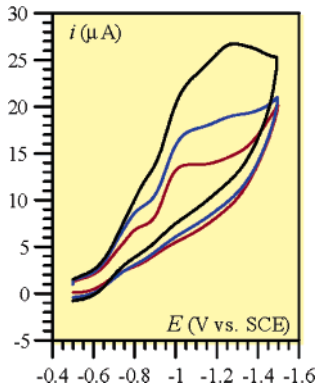
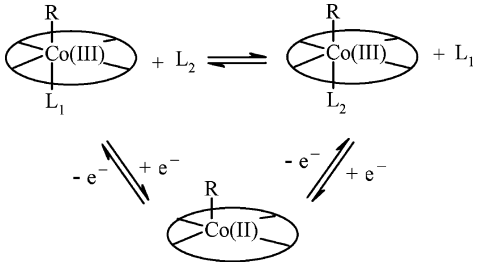


Figure 6. Catalysis of the reduction of chloroacetonitrile by the cobalamin Co(II)/Co(I) couple in DMF + 0.1 M NBu_4ClO_4. Chloroco(III)balamin (1 mM) in the presence of 2 mM $ClCH_2CN$ at different scan rates: 0.05 V/s (red), 0.1 V/s (blue), 0.2 V/s (black).

Scheme 4



which decomposes slowly in the absence of added acid, as discussed in the preceding section. We observed that this second wave splits into two waves as the scan rate is raised in a manner that is typical of a "CE mechanism",[30] which is related to axial ligation as represented in Scheme 4. In the case where L_2 is a ligand more strongly coordinating than L_1, the Co(III)L_2 complex is more difficult to reduce than the Co(III)L_1 complex. If the ligands L_1 and L_2 are present in comparable amount in the solution, the left-hand reduction pathway is disfavored in terms of equilibrium ratio but occurs at a more favorable potential. At this potential, not only the equilibrium amount of the Co(III)L_1 complex is reduced but also what is regenerated kinetically from the Co(III)L_2 complex. This kinetic regeneration competes with diffusion, the rate of which is related to the scan rate. Thus at low scan rate, all reduction may occur through the Co(III)L_1 complex, whereas upon raising the scan rate, part of the reduction occurs in this way and the remainder of the Co(III)L_2 complex is reduced at a more negative potential, making a new, more negative wave appear. This is what is observed in Figure 6, L_1 being the benzimidazole ligand attached to the corrin ring (Chart 1) and L_2 being the chloride ion present in the starting chlorocobalamin and generated by the reaction of the Co(I) complex with chloroacetonitrile.[31]

Other indications of the role of chloride ion as axial ligand are provided by experiments carried out in the presence of a large amount of chloride ions (Figures 7 and 8). Although, as emphasized earlier, the reduction of the initial Co(III) complex is not of direct interest to the understanding of the catalytic process, the effect of the axial ligand on its cyclic voltammetric response provides clues on their role in the reduction of Co(III)CH_2CN, since we deal with cobalt(III) complexes in both cases. It is interesting in this connection that acetate ion acts as a strongly coordinating ligand of Co(III) complexes, as can be seen in Figure 7a, where the behaviors of chlorocobalamin and acetatocobalamin are compared. It is seen that the acetate ion is a more strongly coordinating ligand than the chloride ion. The reduction of the acetato−Co(III) complex is so much pushed toward negative potentials that it merges with the Co(II)/Co(I)

(30) (a) Savéant, J.-M.; Vianello, E. *Electrochim. Acta* **1963**, *8*, 905. (b) Andrieux, C. P.; Savéant, J.-M. Electrochemical reactions. In *Investigations of Rates and Mechanisms of Reactions, Techniques in Chemistry;* Bernasconi, C., Ed., J. Wiley and Sons: New York, 1986; Vol. 6, 4/E, Part 2, pp 305−390.

(31) To decide whether reactant and product adsorption could be the cause of the observed potential shifts and wave splitting, several experiments were run changing the supporting electrolyte, the concentration of the supporting electrolyte, the solvent, and the concentration of the reactants. Neither the use of DMSO as solvent nor the use of higher concentrations of supporting electrolyte in DMF gave any change in the peak potential of the catalytic wave. The same results were also observed using different supporting electrolytes (tetraethyl-, tetrabutyl-, and tetrahexylammonium perchlorates), and finally no significant changes in the maximum of the catalytic peak were obtained on going from 0.25 to 1 mM concentration of chlorocobalamin.

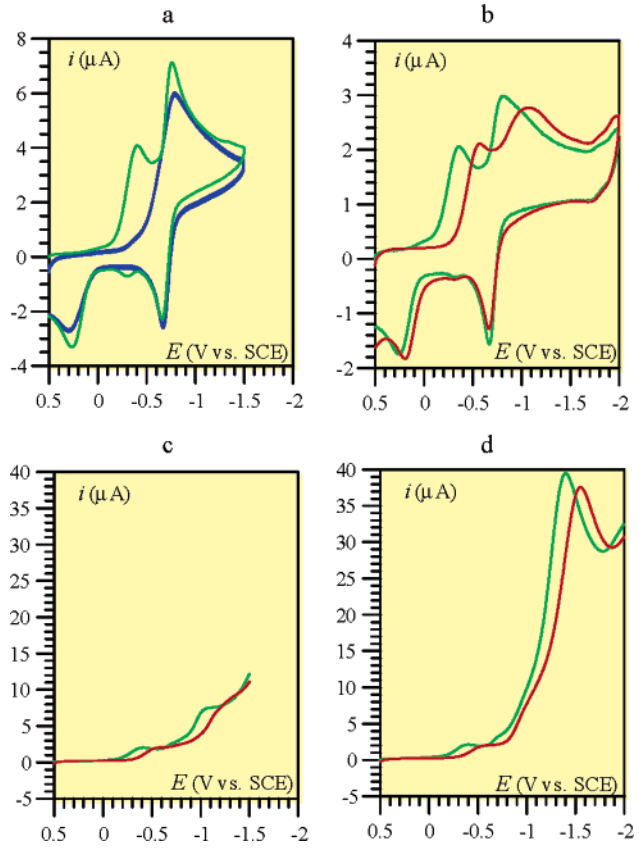


Figure 7. Catalysis of the reduction of chloroacetonitrile by the cobalamin Co(II)/Co(I) couple in DMF as a function of the presence of Cl^- and $CH_3CO_2^-$ serving as axial ligand: (a) 1 mM chloro- (green) and acetato- (blue) cobalamin; (b) 0.5 mM chlorocobalamin in the presence of 0.1 M NBu_4ClO_4 (green) or 0.1 M NBu_4Cl (red); (c) 0.5 mM chlorocobalamin in the presence of 2 mM $ClCH_2CN$ and 0.1 M NBu_4ClO_4 (green) or 0.1 M NBu_4Cl (red); (d) 0.5 mM chlorocobalamin in the presence of 2 mM $ClCH_2CN$, 50 mM CH_3CO_2H, and 0.1 M NBu_4ClO_4 (green) or 0.1 M NBu_4Cl (red). $v = 0.05$ V/s.

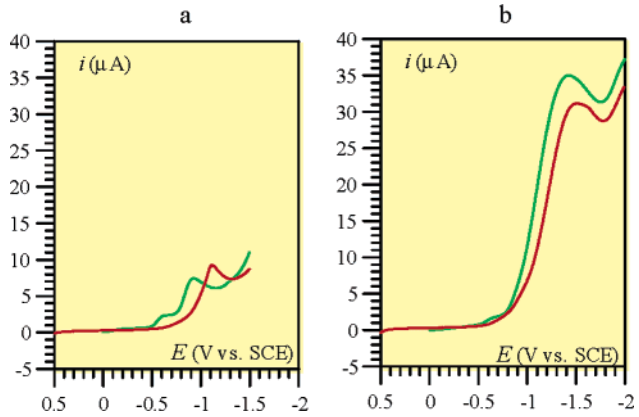
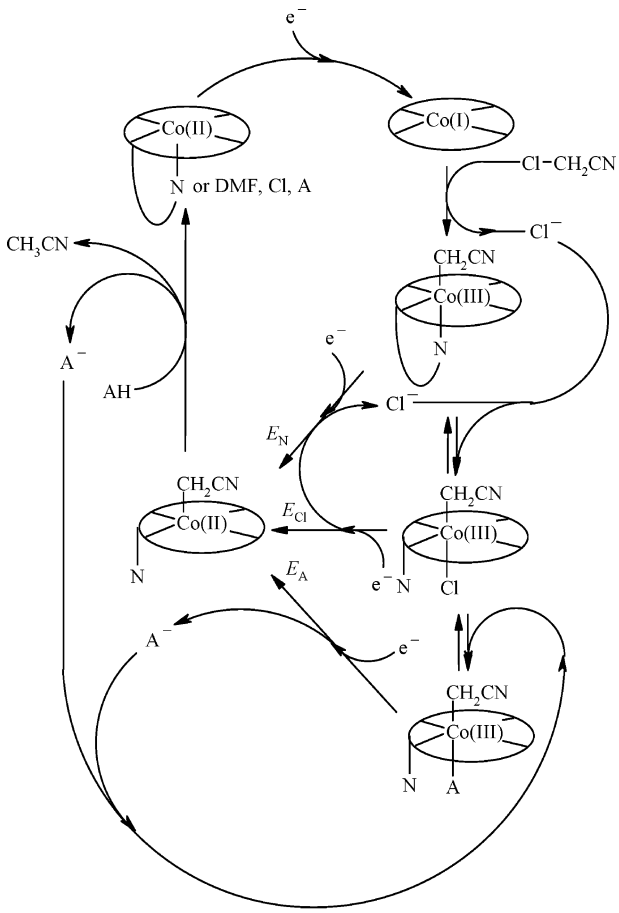


Figure 8. Catalysis of the reduction of chloroacetonitrile by the cobinamide Co(II)/Co(I) couple in DMF as a function of the presence of Cl^- and $CH_3CO_2^-$ serving as axial ligand: (a) 0.5 mM cobinamide in the presence of 2 mM $ClCH_2CN$ and 0.1 M NBu_4ClO_4 (green) or 0.1 M NBu_4Cl (red); (b) 0.5 mM cobinamide in the presence of 2 mM $ClCH_2CN$, 50 mM CH_3CO_2H, and 0.1 M NBu_4ClO_4 (green) or 0.1 M NBu_4Cl (red). $v = 0.05$ V/s.

wave. We thus expect that the acetate ion generated upon catalytic reduction of chloroacetonitrile in the presence of acetic acid likewise serves as axial ligand to the $Co(III)CH_2CN$ complex, thus displacing the catalytic wave toward negative potentials.

Scheme 5



$E_N > E_{Cl} > E_A$ are the reduction potentials of the three alkylCo(III) complexes

Figure 7b shows how the introduction of a much larger amount of chloride ions than present in the initial chlorocobalamin triggers a large negative shift of the Co(III)/Co(II) wave. The introduction of the same large amount of Cl^- likewise provokes a negative shift of the $Co(III)CH_2CN/Co(II)CH_2CN$ wave (Figure 7c) and of the catalytic wave when acetic acid is added to render the $Co(III)CH_2CN$ catalytic (Figure 7d). Figure 8 shows that similar phenomena appear with cobinamide as well.

The more accurate version of the reaction mechanism depicted in Scheme 5 ensues.

Experimental Section

Chemicals. *N*,*N*′-Dimethylformamide (Fluka, >95%, stored on molecular sieves), chloroacetonitrile (Aldrich 99%), hydroxocobalamin hydrochloride (Aldrich 98%), hydroxocobalamin acetate salt (Aldrich), acetic acid (Prolabo, Normapur), supporting electrolyte NBu_4ClO_4 (Fluka, puriss), and NBu_4Cl (Aldrich 97%) were used as received. Diaquocobinamide was prepared from hydroxocobalamin hydrochloride through the following procedure.[32] The nucleotide chain is hydrolyzed under basic conditions following a protocol adapted from the procedure described by Hogenkamp.[33] Hydroxocobalamin hydrochloride (40 mg) is treated with 3 mL of cerium hexanitrate and 2.5 mL of 1 N NaOH. The mixture is heated during 2.5 h (reflux). Then, the solution is filtered and washed with water, the final volume being 130 mL. An extration with phenol following Barker's method is performed:[34] 20 mL of H_2O-

(32) Lexa, D. Personal communication.
(33) Pailes, W. H.; Hogenkamp, H. P. *Biochemistry* **1968**, *7*, 4160.

phenol (15/85) is added to the 130 mL of water solution. The aqueous phase is washed three times with 5 mL of the H_2O−phenol (15/85) solution. Ether (66 mL) and acetone (22 mL) are added to increase the solubility of cobinamide in the aqueous phase. The organic phase is extracted three times with water (3.3 mL). The aqueous phase is washed with ether to remove the remaining phenol. Ether is removed with an argon stream. Finally, the cobinamide is purified on a Sephadex G10 column (0.8 × 120 cm) equilibrated with water. The elution is performed with perchloric acid (pH = 2.5): 7 drops per second. The purification is followed by UV spectroscopy.

Instrumentation. The working electrode was a 3 mm-diameter glassy carbon electrode disk (Tokai) that was carefully polished and ultrasonically rinsed in absolute ethanol before use. The counter electrode was a platinum wire and the reference electrode an aqueous SCE electrode. All experiments have been done at 20 °C, the double-wall jacket cell being thermostated by circulation of water. Cyclic voltammetric data were recorded using a commercial computer controlled potentiostat (AUTOLAB PGSTAT20, ECO-Chemie).

Concluding Remarks

Cobalt corrinoids such as chlorocobalamin or diaquocobinamide are efficient catalysts of the hydrogenolysis of aliphatic chloro compounds. Taking chloroacetonitrile as example, a first requirement for high catalytic efficiency is fulfilled by the high reactivity of the Co(I) complex toward the substrate, leading to the alkylcobalt(III) complex. This is further reduced into the alkylcobalt(II) complex. However, the fact that these two reactions are fast is not enough to ensure an efficient catalysis: in DMF catalysis is very poor, while it is high in water. The experiments carried out in DMF with addition of an acid have shown that a crucial step in the catalytic process is the proton-transfer decomposition of the alkylcobalt(II) complex, leading to the hydrogenolysis final product, and closing the catalytic loop by regeneration of the cobalt(I) complex.

Another important feature of these catalytic reactions is the role played by axial ligands present in the solution, particularly those that are produced by the catalytic reaction itself, namely, chloride ions and the counteranion of the added acid. The more strongly coordinating these ligand, the more negative the potential required for the reduction of the alkylcobalt(III) complex. This amounts to a self-inhibition or, better yet, a self-moderation effect: the more efficient the catalysis, the slower its second step, i.e., the conversion of the alkylcobalt(III) complex into the alkylcobalt(II).

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JA042940F

(34) Barker, H. A.; Smyth, R. D.; Weissbach, H.; Munch-Petersen, A.; Touhey, J. I.; Ladd, J. N.; Volcani, B. E.; Wilson, R. M. *J. Biol. Chem.* **1960**, *235*, 181.