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A New Organocobalt Complex Containing a Co−N−C Three Membered Ring

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Treatment of R = $-CH_2X$ (X = halogen) derivatives of the type $[RCo^{III}(LNH\text{-}py)(HLNH\text{-}py)]^+$, where HLNH-py = 2-(2-pyridyl-ethyl)amino-3-butanone oxime and LNH-py its conjugated base with diluted NaOH, afforded a new complex containing a three-membered ring by a pathway involving the intramolecular nucleophilic addition of an equatorial nitrogen donor to the axial carbon. The X-ray analysis reveals a highly distorted structure. The C−Co−N angle is acute (42.8°) with the distortion of the coordination sphere concentrated in the Co−C axial and Co−N bonds, which move away from the pseudo-octahedral positions in the CH_2X parent complex to form the C−N bond of the metallocycle. Kinetic studies of the formation of this novel complex starting from $[(XCH_2\text{-}Co^{III}(LNH\text{-}py)(HLNH\text{-}py)]^+$ (X = Cl,Br,I) showed that the metallocycle formation rates increase in the order Cl < Br < I. Kinetic data are consistent with a mechanism involving an intermediate species resulting from the deprotonation of an amine equatorial nitrogen in a rapid preequilibrium, followed by the slow step of the ring closure.

Introduction

We have recently reported[1] the synthesis, structural characterization, and solution properties of a new class of organocobalt complexes of the type $[RCo^{III}(LNH\text{-}py)(HLNH\text{-}py)]^+$ (R = Me, Et, CH_2CF_3, n-Bu, CH_2Cl, HLNH-py = 2-(2-pyridyl-ethyl)-amino-3-butanone oxime (Figure 1) and LNH-py its conjugated base derived from the deprotonation of the oxime group).

The study has been directed to assessing the role of the chelating system in stabilizing the Co−C bond. Results have shown that the tridentate imino/oxime ligands possess similar Co−C bond stabilizing ability of that manifested by the tetradentate chelating systems present in the vitamin B_{12} models. In addition, the axial bond distances Co−C and Co−N in the methyl derivative have been found to be very close to those reported for methylcobalamin, making these complexes structural models better than any other previously reported. Thus we expect that the availability of this novel series of organocobalt complexes might provide opportunity to gain further insights into the cobalt−carbon chemistry.

Organometallic Cobalt complexes have been shown to display a wide-ranging reactivity which includes the alkyl transfer reactions, the thermal and photochemical processes of the cobalt−carbon bond cleavage and the insertion reactions of small molecules such as O_2 and SO_2 into metal-alkyl bonds. These aspects have been extensively investigated.[2−5] On the contrary, the chemistry of the carbon bound to the cobalt has rarely been explored previously and pertinent studies are limited to the reactivity of the halogenoalkyl derivatives. For instance the α-chloro- and the α-bromo- alkylcobaloximes, when reacted with sodium borohydride[6] have been shown to generate non-halogenated alkyl-derivatives (eq 1).

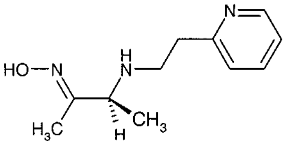

Figure 1.

$$R(X)CHCo^{III}(DH)_2Py \xrightarrow[\text{excess}]{NaBH_4} RCH_2CO^{III}(DH)_2Py \qquad (1)$$

The enzymatic reduction of the difluorocobalamin[7] to methylcobalamin shows some resemblance with the above process, but different mechanisms have been proposed in the two cases. When (trifluoromethyl) cobamides (CF_3Cb) are treated with chemical reductants such as zinc, borohydryde or subjected to controlled-potential reduction give the corresponding (difluoromethyl) cobamides (CF_2HCb) and the alkylated cobamides.[8]

The alkylcobaloxime containing the $-CH_2OCH_3$ group can be produced in the following equation, which again involves the participation of a halogenoalkyl derivative:[9]

$$BrCH_2Co^{III}(DH)_2Py + CH_3O^- \rightarrow CH_3OCH_2Co^{III}(DH)_2Py + Br^- \qquad (2)$$

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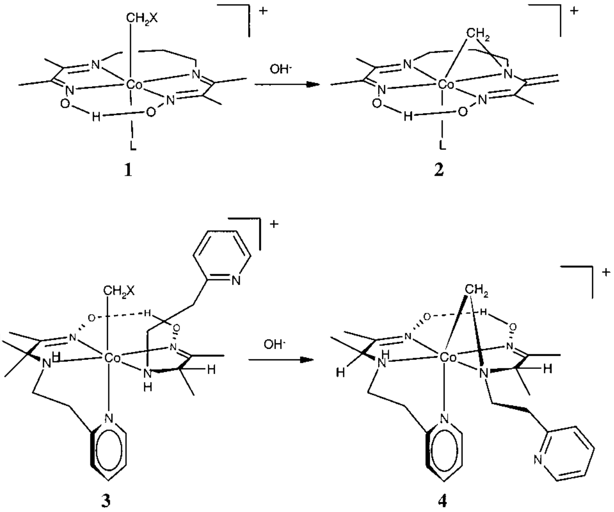

Figure 2.

It has been recently reported[10] that the halogenoalkyl derivative[5] of the type $[XCH_2Co^{III}(DO)(DOH)pnL]^+$ (**1**), in alkaline medium afford the species $[LCo^{III}(N-CH_2-CHEL)]^+$ (**2**), ($N-CH_2-CHEL$ = modified (DO)(DOH)pn macrocycle). As shown in Figure 2, a N−Co−C tree-membered ring was formed through a pathway involving an interligand addition of an equatorial nitrogen donor to at the axial carbon of **1**. The nature of the product suggests that the deprotonation of an imine methyl group $N{=}C-CH_3$ of the equatorial ligand[11] to yield a deprotonated enamine intermediate, $-N-C{=}CH_2$, precedes the ring closure. N-alkylation of the above type has been observed[12] to occur also in some other halogenoalkyl compound having more complicate imino/oxime ligands than that present in **1**.

We have found that the $[ClCH_2Co^{III}(LNH\text{-}py)(HLNH\text{-}py)]^+$ (**3a**) and the related $BrCH_2-$ (**3b**) and ICH_2- (**3c**) halogenoalkyl complexes, when treated with diluted alkali at room temperature, give the same product **4** (Figure 2) containing an intramolecular three-membered metallocycle of the same type above-described, according to eq 3.

$$[XCH_2Co^{III}(LNH\text{-}py)(HLNH\text{-}py)]^+ + OH^- \rightarrow$$

$$[\overline{CH_2Co^{III}(LNH\text{-}py)(HLN}\text{-}py)]^+ + X^- + H_2O \qquad (X = Cl, Br\ or\ I) \quad (3)$$

In the present work we report the synthesis, the X-ray structure and the mechanism of the formation of this new complex from compounds **3**. Significative differences are observed in the reaction patterns leading to the formation of the metallocycle in the present case as compared with the previously reported one,[10] as a consequence of the inherent diversities in the structural properties of the chelating systems.

Results and Discussion

Synthesis. The synthetic route leading to the alkylcobalt compounds involves the in situ generation of a Co^I species starting from compound $[Co^{III}(LNH\text{-}py)(HLNH\text{-}py)]^{2+}$ and successive addition of the appropriate alkyl halide. The reactions were performed in alkaline methanolic solution (NaOH) and under nitrogen atmosphere.

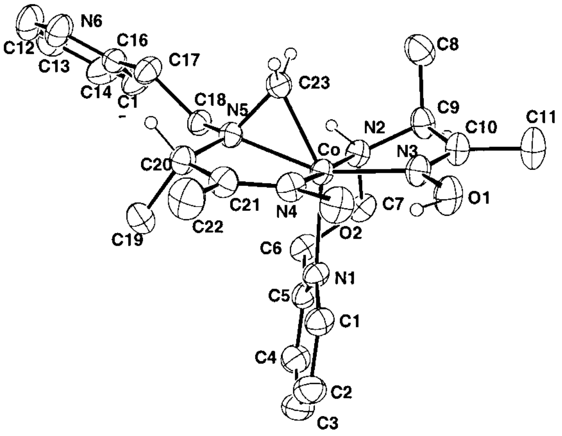

Figure 3. ORTEP diagram with the numbering scheme for the non-hydrogen atoms of **4**.

Table 1. Alkylcobalt Complexes Obtained Using Poly halogenated Hydrocarbons as Alkylating Agents

alkylhalide	expected product	complexes isolated
ICH_2Cl	$[Co]-CH_2Cl$	$[Co]-CH_2Cl$ + **4**
$BrCH_2Br$	$[Co]-CH_2Br$	**4**
ICH_2I	$[Co]-CH_2I$	**4**
$ICHCl_2$	$[Co]-CHCl_2$	$[Co]-CH_2Cl$ + **4**

$$[Co^{III}]^{2+} \xrightarrow{NaBH_4/PdCl_2} [Co^I] \quad (4)$$

$$[Co^I] + RX \rightarrow [Co^{III}R]^+ + X^- \quad (5)$$

Previous work[1] has shown that when the MeI, EtI, CF_3CH_2I, n-BuI were used, the alkyl complexes of the type $[RCo^{III}(LNH\text{-}py)(HLNH\text{-}py)]^+$ with R = Me, Et, CH_2CF_3, *n*-Bu can be easily obtained. Now, we observe that unexpected products were formed when some poly-halogenated hydrocarbons, namely ICH_2Cl, $BrCH_2Br$, ICH_2I and $ICHCl_2$, were used as alkylating agents. The results are summarized in Table 1.

Thus the reaction of $[Co^I]$ with ICH_2Cl, together wit the expected $-CH_2Cl$ derivative **3a**, afforded also small amounts of **4**. It can be shown that, the initial product of the reaction, i.e., **3a**, was in situ partially converted in **4**, being the process promoted by OH^- present in the reaction medium (eq 6 and 7). In fact, in a separated experiment, we found that **3a** dissolved in moderately alkaline methanol at room temperature give **4** in quantitative yield.

$$[Co^I] + ICH_2Cl \rightarrow [Co^{III}CH_2Cl]^+ + I^- \quad (6)$$

$$[Co^{III}CH_2Cl]^+ + OH^- \rightarrow \mathbf{4} + Cl^- \quad (7)$$

Both the reactions with $BrCH_2Br$ and ICH_2I afforded **4** as exclusive product. It can be inferred that in the latter cases the initial products of the reactions, i.e., the $BrCH_2-$ and ICH_2- organocobalt derivatives convert in **4**, with a more rapid process than that observed for **3a**.

The reaction with $ICHCl_2$ (attempting to introduce the $-CHCl_2$ group) gives the $-CH_2Cl$ derivative and compound **4**. The reaction pattern may be interpreted assuming that the initially formed $-CHCl_2$ derivative, in excess of $NaBH_4$ undergoes reductive dehalogenation in a similar way as previously reported for the α-haloalkylcobaloximes[6] depicted in

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[10] Polson, S. M.; Hansen, L.; Marzilli, L. G. *J. Am. Chem. Soc.* **1996**, *118*, 4804.

[11] It has shown that the equatorial methyl groups of $CH_3Co(DH)_2H_2O$ are acidic and undergo exchange with solvent deuterons in alkaline DMSO-d_6 − D_2O mixture.[12−15]

[12] Cartáno, A. V.; Ingraham, L. L. *Bioinorg. Chem.* **1977**, *7*, 351.

Table 2. Crystal Data and Structure Refinement for Complex **4**

formula	$C_{23}H_{34}ClCoN_6O_6$	fw	584.94
a	14.422(3) Å	space group	$P2_1/c$ (no. 14)
b	10.643(2) Å	T	293(2) K
c	18.488(10) Å	λ	0.71070 Å
β	111.36(4)°	ρ_{calcd}	1.470 gcm^{-3}
V	2642.9(16) Å^3	μ	0.800 mm^{-1}
Z	4	R1[$I > 2\sigma(I)$][a]	0.0663
		wR2[$I > 2\sigma(I)$][b]	0.1905

[a] $R1 = \sum||F_o| - |F_c||/\sum|F_o|$. [b] $wR2 = \{\sum w(F_o^2 - F_c^2)^2/\sum w(F_o^2)^2\}^{1/2}$.

Table 3. Selected Bond Lengths [Å] and Angles [deg] for Complex 4 and for the Two Crystallographic Nonequivalent Molecules[1] of [MeCo(LNH-py)(HLNH-py)]$^+$

	3d		4
	molecule A	molecule B	
Co−N1	2.134(5)	2.185(5)	2.118(3)
Co−N2	1.996(5)	1.983(5)	2.011(2)
Co−N3	1.888(6)	1.900(6)	1.933(3)
Co−N4	1.888(3)	1.893(5)	1.905(3)
Co−N5	2.018(5)	2.005(5)	1.982(2)
Co−C23	1.960(7)	1.983(7)	1.943(3)
N3−Co−N5	177.9(3)	178.3(2)	156.0(1)
N5−Co−C23	91.6(3)	91.9(3)	42.8(1)
N1−Co−C23	177.3(3)	175.3(3)	150.6(1)
N1−Co−N5	88.7(2)	90.2(2)	107.8(1)
N1−Co−N3	89.2(2)	88.0(2)	95.9(1)
N3−Co−C23	90.5(3)	89.8(2)	113.3(1)
Co−N1−C1	116.9(4)	118.6(4)	120.2(2)
Co−N1−C5	126.4(5)	125.0(4)	122.0(2)

eq 1. The resulting $-CH_2Cl$ complex, in basic medium, is then partially converted in **4**.

$$[Co^I] + ICHCl_2 \rightarrow [Co^{III}CHCl_2]^+ + I^- \qquad (8)$$

$$[Co^{III}CHCl_2]^+ \xrightarrow{NaBH_4} [Co^{III}CH_2Cl]^+ \qquad (9)$$

$$[Co^{III}CH_2Cl]^+ + OH^- \rightarrow \mathbf{4} + Cl^- \text{ (slow)} \qquad (10)$$

Further experiments allowed us to isolate also the complexes $BrCH_2Co^{III}$(LNH-py)(HLNH-py)]$^+$ (**3b**) and ICH_2Co^{III}(LNH-py)(HLNH-py)]$^+$ (**3c**). Satisfactory synthesis of the latter derivatives could be achieved by a simple modification of the general procedure, consisting in the addition of concentrated CH_3COOH to the reaction mixture at once after the formation of the halogenoalkyl derivatives. In such a manner the neutralization of the solution quenches the formation of **4** which is favored in basic medium. Thus, obtaining of **3b** and **3c**, in addition to **3a**, allowed to perform the kinetic study of the formation of the metallocycle starting from each of the three halogenoalkyl compounds.

X-ray Structure. The formation of a rare Co−N−C three-membered cycle leads to the highly distorted structure shown in Figure 3. The coordination polyhedron about Co exhibits severe distortions from octahedral one, similar to those found in the [PyCo(N−CH$_2$−CHEL)]$^+$ (**2**) cation, which has the same three-membered ring[10] with an acute N5−Co−C23 angle of 43.8(2)° very close to that found here of 42.8(1)°.

The N5 atom is displaced by 0.744(4) Å out of the mean plane passing through Co, N2, N3, N4, which are coplanar within ± 0.03 Å. These distortions are apparent when the coordination bond length and angles are compared (Table 3) with those of the "normal" octahedral parent cation [MeCo(LNH−Py)(HLNH−Py)]$^+$ (**3d**) previously studied.[1] The formation of the ring provokes a large narrowing of the N3−Co−N5 and N1−Co−C23 coordination angles of about 20° and 30° respectively as compared with those of the **3d** (Table 3). Conversely, the N1−Co−N5 and N3−Co−C23 angles are widened by about 20°. The remaining coordination angles in the two cations, **3d** and **4**, do not largely differ within more than few degrees, excepted the N1−Co−N3 cycle which is increased of about 8° in **3d**. This comparison shows that the coordination geometry of **3d** is essentially related to that of **4**, by moving nearly in the C−Co−N5 plane N5 upward and C23 downward the equatorial plane to form the N5−C23 bond. This creates a pocket under the Co−N2 bond on the pyridyl side, so that the latter coordinates more easily in a symmetric way to Co in contrast to the "asymmetric" coordination in **4**. In fact the Co−N1−C1 and Co−N1−C5 angles are very similar in **4** and differ by about 10° in **3d** (Table 3). As already observed,[10] in the comparison between **2** and **1**, both the axial Co−C and Co−N bonds in **4** are shorter than the corresponding axial bonds in **3d**. The O···O oximic distance is 2.424 Å comparable with that of 2.401(7) in **3d** but shorter than that of 2.487(2) obtained by averaging 140 values found in cobaloximes.[2]

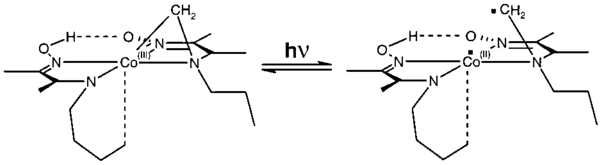


Figure 4.

Cobalt−Carbon Bond Stability. The aspects concerning the reactivity of compound **4** will be treated in a further paper. However at least one observation has to be anticipated:

It is well-known that alkylcobalt are light sensitive[4] especially in the presence of oxygen. In aerobic conditions the R-[Co^{III}] complexes are assumed to produce as initial products [Co^{II}] and •R radicals, which in the presence of oxygen, give the corresponding aldehyde. Thus the increased Co−C bond homolysis rate in aerobic conditions is attributed to the radicals trapping ability of the molecular oxygen hampering the recombination of the •R and [Co^{II}] radicals. In contrast with the majority of the alkyl cobalt complexes, compound **4** has been found to be light resistant. Its behavior may be interpreted on the basis of the following reaction (Figure 4):

The initially formed radicals are still kept near one to other as imposed by the geometry of the system, so that the radical fragment •CH$_2$−N− prefers to recombine with •Co^{II} radical rather than with oxygen.

Kinetic and Mechanism of Formation of Complex 4. Kinetics of conversion of **3a**, **3b** and **3c** in **4** were followed spectrophotometrically by means a stopped-flow apparatus in alkaline solution at 25 °C. Each reaction was studied with a pseudo-first-order excess of [OH$^-$] over the complex. The other conditions are described in the Experimental Section. The observed rate constants corresponding to the first-order kinetics in complex (k_{obsd}, s^{-1}) have been analyzed as a function of [OH$^-$]. For each of the compounds the form of the k_{obsd} was found to be of the type (eq 11):

$$k_{obsd} = a[OH^-] + b[OH^-]^2 \qquad (11)$$

This is represented in Figure 5.

The form of the k_{obsd} (eq 11) suggests the multistep mechanism depicted in Scheme 1, where the first step corresponds to the fast deprotonation of the aminic N bearing the pendant

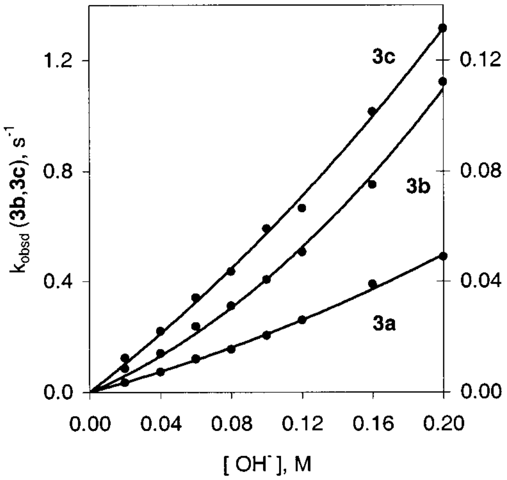
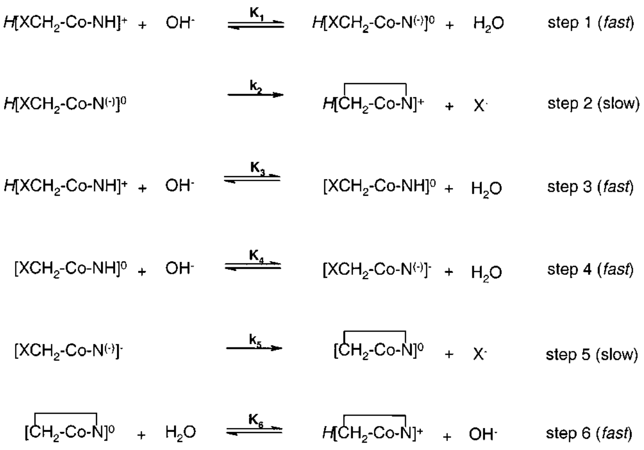


Figure 5. Fitting of the k_{obsd} vs $[OH^-]$ for the formation of **4** from **3a**, **3b**, and **3c**. Data collected at 25 °C and ionic strength 0.2 M ($NaClO_4$).

Scheme 1 [a]



[a] Legend to the scheme: the complexes formulas are abbreviated as follows: $H[XCH_2Co\text{-}NH]^+$ represents the starting complexes **3a**, **3b** and **3c**. $H[XCH_2Co\text{-}N^{(-)}]^0$ their conjugated bases derived by deprotonation of the equatorial nitrogen. $H[\overline{CH_2Co\text{-}N}]^+$ the final product. $[XCH_2Co\text{-}NH]^0$ the complex deprotonated at the hydrogen bridge. $[XCH_2Co\text{-}N^{(-)}]^-$ its conjugated base derived by successive deprotonation to the equatorial nitrogen. $[\overline{CH_2Co\text{-}NH}]^0$ the final product deprotonated at the hydrogen bridge. The italic *H* represents the hydrogen of the equatorial hydrogen bridge.

pyridyl group. The slow nucleophilic addition of the equatorial nitrogen to the axial carbon follows (step 2). The latter reaction involves inversion of configuration to the nitrogen (Figure 2). The second order in OH^- (eq 11) is consistent with the presence of a further acid−base equilibrium. Tentatively, it is identified in the reversible deprotonation of the OH···O bridge (step 3). Acid−base equilibrium of this type have been observed to occur in cobaloximes and in related complexes containing hydrogen bonds in their chelating systems.[17,18] This intermediate species undergoes further deprotonation (to the aminic nitrogen) (step 4) preceding the slow closure of the ring (step 5). The final product is formed in step 6 in a rapid acid−base equilibrium, with reformation of the O−H···O bridge.

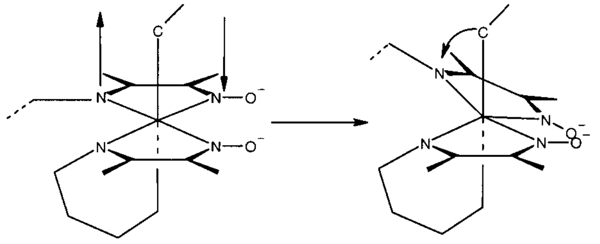


Figure 6. Proposed distortional step showing the approaching of one equatorial N atom to the axial carbon.

Table 4. Kinetic Data for the Formation of **4** from **3a**, **3b**, and **3c** at 25 °C and Ionic Strength 0.2 M ($NaClO_4$)

R	k_1K_2, $s^{-1}M^{-1}$	$K_3K_4k_5$, $s^{-1}M^{-2}$
CH_2Cl	0.17 (±0.01)	0.40 (±0.06)
CH_2Br	2.69 (±0.28)	13.95 (±1.77)
CH_2I	4.93 (±0.28)	8.20 (±1.73)

From the above scheme, under the assumptions that steps 1, 3 and 4 are fast preequilibrium and the equilibrium 6 is essentially shifted on the right, and taking into account the experimental conditions (i.e. large excess of $[OH^-]$ over the concentration of the complex) the following equation for the k_{obsd} may be derived:

$$k_{obsd} = \frac{k_2K_1[OH^-] + k_5K_3K_4[OH^-]^2}{1 + (K_1 + K_2)[OH^-] + K_3K_4[OH^-]^2} \qquad (12)$$

Assuming $(K_1 + K_3)\ [OH^-] + K_3K_4[OH^{-]2} \ll 1$ (i.e., K_1, K_3, and K_4 very small), eq 12 becomes:

$$k_{obsd} = k_2K_1\ [OH^-] + k_5K_3K_4\ [OH^-]^2 \qquad (13)$$

Which conforms the experimental data (eq 11) with $a{\equiv}k_2K_1$ and $b{\equiv}k_5K_3K_4$. Kinetic data for X = Cl, Br and I are collected in Table 4.

Assuming that K_1 values are not significantly affected by the nature of the halogen in the CH_2X group, the ratio of the k_2K_1 values may reflect the relative rate of the ring closure.

The k_2K_1 ratio results to be: Cl: Br: I = 1:16:29. Interestingly, the same trend, i.e., Cl/Br/I = 1:14:91, has been reported for rate constants ratio found for the solvolisys of 1-Phenylethyl halides and explained in terms of relative leaving group ability of X.[19] This analogy suggests that in complexes **3** the rate of the metallocycle closure may be related to the C−X bonds strength: a slower C−N bond formation being consistent with a greater strength of the C−X bond. This requires that step 2 in Scheme 1 is rate-limiting. It would be expected that the ring closure rates also depend, at some extent, on the X halogen bulk, hampering the approach of the nitrogen to the target carbon in the increasing order: Cl < Br < I. Probably this steric effect is reflected by the Br: I rate constants ratio higher than that expected as compared to that found in the 1-phenylethylhalides hydrolysis.

The second order with respect to $[OH^-]$ (eq 11) can be justified by assuming the formation of an intermediate species, resulting from the deprotonation of both the OH···O hydrogen bond and equatorial nitrogen in **3** (step 3 and 4 in Scheme 1). Thus, in absence of constraint due to the equatorial hydrogen bond, the distortion of the equatorial ring might be facilitated

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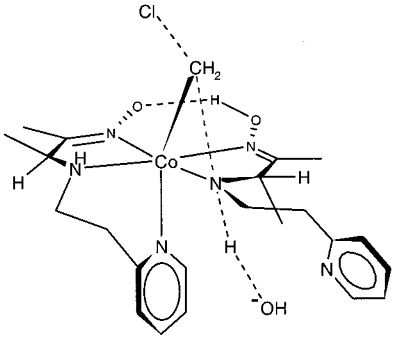

Figure 7.

allowing a better approach of the deprotonated sp^3 nitrogen to the target axial carbon (Figure 6).

In a similar way the reaction of **1** to give **2** has been proposed to involve a "distortion step" leading to a favorable conformation of the chelating system for the C−N bond formation.[10]

The $k_5K_3K_4$ product ratio, associated to the quadratic term in [OH$^-$], results to be Cl/Br/I = 1:35:20. The disagreement with the trend observed for the k_2K_1 ratio, i.e., Cl < Br < I is unexpected it is difficult to explain. Previous works have shown that the pK_a values for the acid−base processes involving the hydrogen bond in the cobaloximes are influenced by the nature of the axial ligands. In a similar way CH_2X group would influence the deprotonation of the hydrogen bridge (K_3) of complexes. But it can be also expected that the changes of X would have a minor effect on the oxime O-deprotonation than on N-deprotonation, leaving, in this hypothesis, unchanged the order Cl < Br < I. Consequently on the basis of merely electronic effects the odd order for $k_5K_3K_4$ cannot be unambiguously justified.[17,18]

We can also consider an alternative mechanism. It can be supposed that the metallocycle may form with a concerted process, which do not involve the preliminary deprotonation step of the amino equatorial group. For such a mechanism the transition state depicted in Figure 7 can be proposed.

Under this hypothesis the pairs of steps 1−2 and 4−5 of the Scheme 1 are replaced by the step 2′ and 5′.

$$H[\mathrm{XCH_2{-}Co{-}NH}]^+ + \mathrm{OH}^- \xrightarrow{k'_2} H[\overline{\mathrm{CH_2{-}Co{-}N}}]^+ + \mathrm{X}^- + \mathrm{H_2O} \quad \text{(step 2′)}$$

$$[\mathrm{XCH_2{-}Co{-}NH}]^0 + \mathrm{OH}^- \xrightarrow{k'_5} [\overline{\mathrm{CH_2{-}Co{-}N}}]^0 + \mathrm{X}^- + \mathrm{H_2O} \quad \text{(step 5′)}$$

where k'_2 and k'_5 rate constants correspond to K_1k_2 and K_4k_5 of the Scheme 1.

Thereby, the eq 12 becomes

$$k_{\mathrm{obsd}} = k'_2\,[\mathrm{OH}^-] + k'_5K_3[\mathrm{OH}^-]^2 \tag{14}$$

which alike eq 13 conforms the experimental data (see eq 11), so that the two mechanisms are not kinetically distinguishable.

Concluding Remarks

It is apparent that the metallocycle formation is even more facile in **3** than in **1**. In both cases generation of the nucleophilic negatively charged nitrogen is required. However, in complexes **3** this occurs by the simple removal of a proton from the nitrogen itself, whereas in the imino/oxime compounds a more difficult removal of a proton from an equatorial $-CH_3$ group, far from the reactive center, is necessary.

It is also interesting that the metallocycle formation involves N5 instead N2 of **3**, which appears to be sterically more appropriate to form it (see structure). In fact, the metallocycle closure through N2 would not require conformation inversion, which on the contrary is observed to occur at N5. On the other hand it could be observed that N2, has less possibility than N5 to move toward the target carbon, being constrained in its position by the axially coordinated pyridyl group.

The metallocycle formation can be seen as the first step of a one-carbon unit transfer from the Co to an organic substrate, here the equatorial ligand. It would be of interest to find out the appropriate experimental conditions (possibly a mild treatment) for the Co−C bond cleavage in such a way to achieve the complete transfer on the ligand. However, qualitative observations, under conditions for which Co−C bond photolytic cleavage is observed to occur in the alkylcobalt complexes,[4] indicate that **4** is unusually photostable. It must also take into account that a short Co−C bond length is consistent with a strong metal−carbon bond: the Co−C bond length of 1.943(3) in **4** is significantly shorter than that found in the undistorted methylderivative (mean value of 1.972(7) Å for the two crystallographically nonequivalent molecules, (Table 3). Thus, it may be expected that attempts to cleave Co−C bond in **4**, under mild conditions, would have scarce chances of success.

No evidence has been so far reported for the formation of a similar metallocycle in the cobalamins. However if an analogous reaction can be demonstrate for these compounds, this would lead to the speculation that the resulting inert species may limit the catalytic turnover in the biological processes. In fact, homolysis of the Co−C bond of B_{12} enzymes is generally accepted to be an essential step in the enzymatic reactions for which the coenzyme B_{12} is the cofactor.[5]

Experimental Section

Instruments and Materials. NMR spectra were recorded with a JEOL EX-400 (^{1}H at 400 MHz and ^{13}C at 100.4 MHz) from DMSO-d_6 solutions with TMS as internal standard. UV/vis spectra and kinetics were performed by a Perkin-Elmer Lambda 5 spectrophotometer and by a Hi-Tech stopped-flow apparatus. Commercially available chemicals were purchased and used without further purification.

Syntheses. All the complexes were isolated as perchlorate salts. **CAUTION:** *Although no problems were encountered in the present study, perchlorate salts are potentially explosive and should only be handled in small quantities!*

$ClCH_2-Co^{III}$(LNH-py)(HLNH-py)]ClO_4 (3a). Synthesis, elemental analysis data and NMR characterization for this compound have been reported elsewhere.[1]

$BrCH_2-Co^{III}$(LNH-py)(HLNH-py)]ClO_4 (3b). A slightly modified method of synthesis, with respect to that used for **3a**, was adopted in this case. A solution of NaOH (0.2 g, 5 mmol) in 2 mL of water was added to a suspension of complex[1] [Co^{III}(LNH-py)(HLNH-py)]$^{2+}$ (1 g, 1.49 mmol) in 150 mL of methanol under nitrogen atmosphere. The resulting solution was treated with $NaBH_4$ (0.12 g, 4.7 mmol) dissolved in a minimum volume of water, followed by three drops of $PdCl_2$ solution, prepared by addition of concentrated HCl to a suspension of 1 g of $PdCl_2$ in 20 mL of water until complete dissolution. When the solution assumed a dark brown color (after about 15 min), the reaction vessel was immerged in a ice bath and then 0.52 mL (7.45 mmol) of CH_2Br_2 were added. In about 2−3 min. the dark brown solution turned to bright orange. At this point, the flow of nitrogen was suspended and the basic reaction mixture was neutralized with concentrated CH_3COOH. Then methanol was removed by a rotary evaporator at 40 °C and the resulting aqueous suspension was extracted two times with 50 mL of CH_2Cl_2. This solution was concentrated to about 10 mL and passed through a chromatographic column of Al_2O_3. Elution with CH_2-

Cl_2 gave about 50 mL of solution containing the pure product. Isopropyl ether was then added until turbidity and the suspension allowed to stand overnight. Yellow crystals of the product were recovered by filtration and air-dried. Anal. Calcd for $C_{23}H_{35}BrClCoN_6O_6$: C, 41.5; H, 5.30; N, 12.6. Found: C, 41.7; H, 5.29; N, 12.6. ^{1}H− NMR (DMSO-d_6) δH: 0.72, 1.40(6 H, d, 2CH_3−CH); 1.77, 2.05 (6H, s, 2CH_3−C═N); 2.86, 3.37 (8H, m, 2CH_2−CH_2); 3.71, 3.79 (2H, m, 2C*H*−CH_3); 4.80, (2H, s, 2NH); 5.17 (2H, s, CH_2Br); 7.27, 7.32, 7.54, 7.73, 7.76, 8.04, 8.30, 8.40 (8H, 2C_5H_4N); 19.23 (1H, s, OHO).

ICH_2−Co^{III}(LNH-py)(HLNH-py)]ClO_4 (3c). Synthesized as **3b** using CH_2I_2 instead CH_2Br_2. Anal. Calcd for $C_{23}H_{35}ClCoIN_6O_6$: C, 38.8; H, 4.95; N, 11.8. Found: C, 38.6; H, 4.88; N, 11.6. ^{1}H NMR (DMSO-d_6) δH: 0.75, 1.43 (6H, d, 2CH_3−CH); 1.79, 2.08 (6H, s, 2CH_3−C═N); 2.85, 3.35 (8H, m, 2CH_2−CH_2); 3.71, 3.83 (2H, m, 2C*H*−CH_3),4.39, (2H, s, 2NH); 5.26 (2H, s, CH_2I); 7.26, 7.29, 7.51, 7.75, 8.04, 8.06, 8.28, 8.36 (8H, 2C_5H_4N); 19.30 (1H, s, OHO).

CH_2−Co^{III}[LNH-py)(HLN-py)]ClO_4 (4). Synthesis A. A total of 0.2 g of compound **3a** (0.32 mmol) dissolved in a minimum volume of 0.1 M NaOH were allowed to stand overnight at room temperature. The successive addition of some drops of aqueous concentrated $NaClO_4$ induced the formation of the orange crystals of the product, which were collected by filtration and air-dried. The so obtained crystals are suitable for X-ray data collection, without any further recrystallization. Anal. Calcd for $C_{23}H_{34}ClCoN_6O_6$: C, 47.2; H, 5.86; N, 14.4. Found: C, 47.3; H, 5.84; N, 14.3. ^{1}H NMR (DMSO-d_6) δH: 0.55, 1.36 (6H,d, 2CH_3−CH); 1.76, 1.91 (6H, s, 2CH_3−C═N); 3.03, 3.60 (2H, m, 2C*H*−CH_3), 3.66 (1H, s, NH); 3.69, 4.01 (2H, d, Co−CH_2−N); 7.30, 7.44, 7.60, 7.65, 7.78, 8.04, 8.54, 8.87 (8H, 2C_5H_4N); 19.30 (1H, s, OHO).

Synthesis B. Compound **4** can be obtained in almost quantitative yields by using $CHBr_2$ or CHI_2 instead ICHCl and by applying the general method of the synthesis,[1] i.e., the addition of CH_3COOH as quenching agent as in the preparation of **3b** and **3c** was omitted. The product was identified by ^{1}H NMR spectroscopy.

Formation of Compound 4. The liquor mother remaining after precipitation of **3a**[1] treated with *n*-pentane gave after several hours small amount of **4** characterized by ^{1}H NMR spectra.

Reaction with $ICHCl_2$. General method applied to complex[1] [Co^{III}-(LNH-py)(HLNH-py)]$^{2+}$ using $ICHCl_2$ as alkylating agent gave **3a** as main product. The mother liquor solution remaining after precipitation, treated with *n*-pentane gave small amount of compound **4**. Both the products were identified by means ^{1}H NMR analysis.

Photochemical Behavior of Complex 4. A visible cuvette was filled with a $1 \cdot 10^{-4}$ M solution of complex **4** and exposed, in aerobic conditions, to the radiation of a sunlamp. The solution was periodically analyzed by visible spectroscopy. During a 12 h interval the spectrum of the solution remained unchanged. In the same conditions the complex **3d** was photolyzed in about 0.5 h.

Kinetic Experiments. The kinetics of the metallocycle formation starting from **3a**, **3b** and **3c** were monitored spectrophotometrically at 410 nm by means a stopped-flow apparatus at the temperature of 25 ± 0.2 °C. Each reaction was studied with a pseudo-first-order excess of [OH^-]. Typical initial concentrations of the complex were 0.5 10^{-3} M with a variation of [OH^-] from 0.02 to 0.2 M. Ionic strength was adjusted at 0.2 M by $NaClO_4$. The use of $NaNO_3$ as inert salt instead perchlorate did not cause changes in the rate constant values. The digitized transmittance-time data were converted to absorbance (*A*) and then analyzed by a nonlinear least-squares program according to the first-order equation: $A_t = A_\infty + (A_0 - A_\infty)\cdot\exp(-k_{obsd}\cdot t)$, which all runs follow exactly. Some of the slower runs, namely those of the complex **3a** at the lowest OH^- concentrations, could be followed by conventional spectrophotometry using a double beam instrument. The so obtained k_{obsd} values were found to be in excellent agreement with those obtained by the stopped-flow technique at the corresponding OH^- concentrations.

Structure Determination. Single crystals, suitable for X-ray data collection of **4**, were obtained as reported in syntheses. X-ray diffraction data were collected at room temperature with a Nonius DIP1030 H System using graphite-monochromated Mo Kα radiation ($\lambda = 0.71070$ Å). A total of 45 frames were collected, using the Xpress program,[20] over a half of reciprocal space with rotation of 4° about the φ axis. A MAC Science Image Plate (diameter = 300 mm) was used and the crystal-to-plate distance was fixed at 90 mm. The determination of unit-cell parameters, integration of reflection intensities and data scaling were performed using MOSFLM and SCALA from the CCP4 program suite.[21] Reflections, which were measured on previous and following frames, were used to scale the frames on each other, a procedure that partially eliminated absorption effects, taking into account also any crystal decay. The structure was solved by Patterson methods followed by Fourier syntheses and refined by full-matrix least-squares (on F^2) cycles. The H atoms were not refined but included at calculated positions in the final refinement. All the calculations were carried out with SHELXS (Solution of structures) and SHELXL (Refinement of structures) programs.[22,23] A suite of programs[24] was also used in the geometrical and final calculation. Table 2 reports a summary of data collection procedures and crystallographic statistics.

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Supporting Information Available: X-ray crystallographic files in CIF format for the structure determination of **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

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