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# Organometallic Complexes Containing a Co−N−C Three-Membered Ring: Factors Affecting the Dynamic of the Ring Closure

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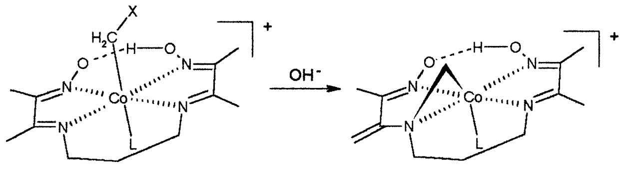
Treatment of $[ClCH_2Co^{III}(L_1NH\text{-}py)(HL_1NH\text{-}py)]ClO_4$, where $HL_1NH$-py is the tridentate 2-((2-pyridylmethyl)amino)-3-butanone oxime and $L_1NH\text{-}py^-$ its conjugated base with diluted NaOH, afforded the new complex $[CH_2Co^{III}(L_1NH\text{-}py)(HL_1N\text{-}py)]ClO_4$, containing a three-membered metallacycle by a pathway involving the intramolecular nucleophilic addition of an equatorial nitrogen donor to the axial carbon. The X-ray analysis revealed a highly distorted structure with the distortion concentrated in the Co−C bond. The kinetics of formation of this complex and of the analogous complexes (previously synthesized) containing the 2-((2-(2-pyridyl)ethyl)amino)-3-butanone oxime ligand (HLNH-py) were studied. These studies revealed that the intramolecular process forming the metallacycle is quite rapid, whereas the carbon atom bonded to cobalt is inert toward nucleophilic intermolecular attack. The rapidity of the reaction was ascribed to a favorable entropy contribution and to the "proximity effect" imposed by the relatively rigid framework of the molecule, which holds together the reactive centers (C and N atoms) within a critical distance.

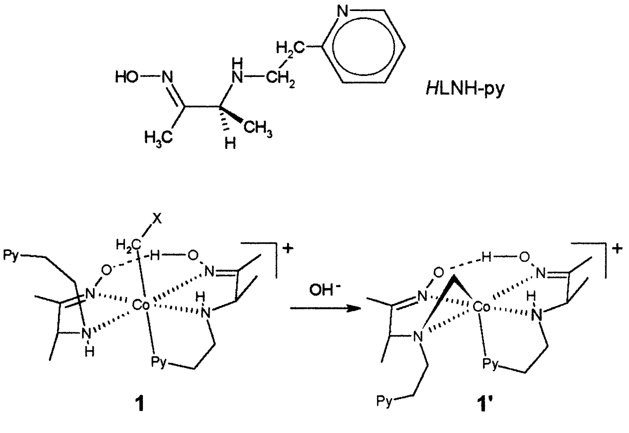
## Introduction

Cobalt(III) chelates containing a $Co-CH_2-N$ intramolecular three-membered metallacycle were discovered by Marzilli and co-workers in 1994. These authors have shown that halogenoalkyl derivatives of the type $[XCH_2Co^{III}(DO)(DOH)pnL]^+$ in alkaline medium afford the species $[LCo^{III}(N-CH_2-CHEL)]^+$, where $N-CH_2-CHEL$ is the modified (DO)(DOH)pn macrocycle.[1] Similar behavior was found also for some closely related complexes.[2] The X-ray structure of the pyridine (L = py) derivative $[pyCo^{III}(N-CH_2-CHEL)]^+$ reveals the presence of a $-CH_2-$ group linking the cobalt atom to an equatorial nitrogen and an enamine ($N-C{=}CH_2$) in place of one imine moiety ($N{=}C-CH_3$) present in the starting complex. These structural features suggest that the reaction (Scheme 1) involves the deprotonation of one equatorial methyl group to yield a deprotonated enamine intermediate followed by the nucleophilic addition of the equatorial nitrogen donor to the ligated axial carbon.

**Scheme 1**



**Scheme 2**



Later, we reported that monocations of the type $[XCH_2Co^{III}(LNH\text{-}py)(HLNH\text{-}py)]^+$ (**1**), where X = Cl, Br, I and HLNH-py = 2-((2-(2-pyridyl)ethyl)amino)-3-butanone oxime (Scheme 2) and LNH-py is its conjugated base, when treated with dilute alkali, gives the $[CH_2Co^{III}(LNH\text{-}py)(HLN\text{-}py)]^+$ (**1′**) complex containing an intramolecular metallacycle of the type described in Scheme 2.[3] Preliminary kinetic studies suggested that the overall reaction scheme involves the deprotonation (in a fast preequilibrium step) of the amino equatorial NH group bearing the noncoordinated $-CH_2CH_2$-py fragment, followed by ring closure, which is the slow step.[3] The reaction occurs with inversion of configura-

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(1) Polson, S. M.; Hansen, L.; Marzilli, L. G. *J. Am. Chem. Soc.* **1966**, *118*, 4804.

(2) Marzilli, L. G.; Polson, S. M.; Hansen, L.: Moore, S. J.; Marzilli, P. A. *Inorg. Chem.* **1997**, *36*, 3854.

(3) Dreos, R.; Felluga, A.; Nardin, G.; Randaccio, L.; Siega, P.; Tauzher, G. *Inorg. Chem.* **2001**, *40*, 5541.

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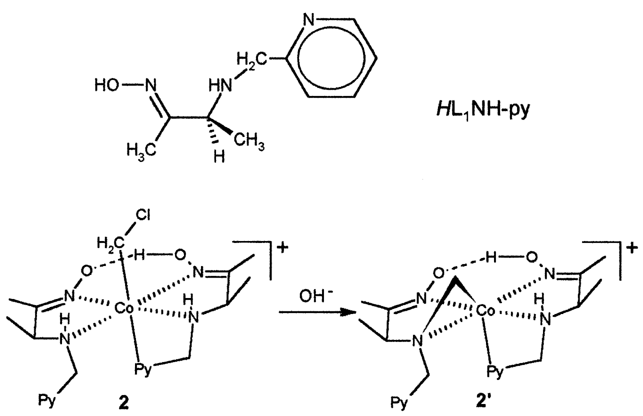
**Scheme 3**



tion at the nitrogen atom (Scheme 2). It was also found that the intramolecular cyclization reaction is quite fast, in contrast with the inertness of the halogenoalkyl group linked to the cobalt atom toward attack of external nucleophilic agents. However, the data so far acquired are not sufficient to give a reliable picture of the transition state. Furthermore, the factors influencing the reaction rate are still unclear. In the present paper we report detailed kinetic studies about the intramolecular reaction forming complex **1′**. In addition, we report the synthesis and the structural characterization of a new metallacycle-containing complex. Kinetic data for the latter complex are also reported and compared with those of complex **1′**.

## Results

**Syntheses and Characterization.** The new complex $[\overline{CH_2Co^{III}(L_1NH\text{-}py)(HL_1N}\text{-}py)]ClO_4$ (**2′**) ($HL_1NH$-py is the tridentate 2-((2-pyridylmethyl)amino)-3-butanone oxime and $L_1NH\text{-}py^-$ its conjugated base) was obtained from the parent compound $[ClCH_2Co^{III}(L_1NH\text{-}py)(HL_1NH\text{-}py)]ClO_4$ (**2**) by treatment with dilute NaOH solution (Scheme 3). This ligand differs from that present in **1** and **1′**, in having a shorter ($-CH_2-$ vs $-CH_2CH_2-$) arm linking the pyridyl group to the equatorial moiety. The synthetic procedure[4] for it is similar to that employed in the case of the analogous Me derivative $[MeCo^{III}(L_1NH\text{-}py)(HL_1NH\text{-}py)]^+$, except that $BrCH_2Cl$ instead of MeI was used as alkylating agent.

Unlike the reaction of **1** (Scheme 1), the metallacycle closure in **2** does not involve inversion of configuration to the nucleophilic N atom. Complex **2′** has been characterized by means of X-ray crystallography.

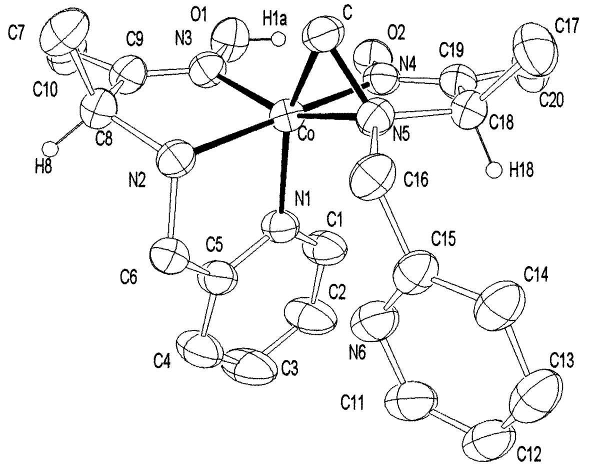


**Figure 1.** ORTEP diagram with the numbering scheme for the molecule of **2′**.

**Table 1. Selected Bond Lengths (Å) and Angles (deg) for Complexes 1″, 2″, 1′, and 2′**

| | **1″**[a] | **2″**[b] | **1′**[c] | **2′** |
|---|---|---|---|---|
| Co−N1 | 2.160(5) | 2.032(4) | 2.118(3) | 2.035(3) |
| Co−N2 | 1.990(5) | 2.010(4) | 2.011(2) | 2.007(3) |
| Co−N3 | 1.894(6) | 1.916(4) | 1.933(3) | 1.927(4) |
| Co−N4 | 1.891(5) | 1.895(5) | 1.905(3) | 1.903(3) |
| Co−N5 | 2.012(5) | 2.044(4) | 1.982(2) | 1.955(4) |
| Co−C | 1.972(7) | 1.994(6) | 1.943(3) | 1.931(4) |
| C−N5 | | | 1.434(4) | 1.438(5) |
| N1−Co−N2 | 92.7(2) | 82.9(2) | 93.9(1) | 83.4(1) |
| N1−Co−N3 | 88.6(2) | 89.1(2) | 95.6(1) | 86.9(2) |
| N1−Co−N5 | 89.5(2) | 94.1(2) | 107.8(1) | 112.4(2) |
| N2−Co−N3 | 82.1(2) | 81.6(2) | 80.8(1) | 81.8(1) |
| N2−Co−N4 | 176.1(2) | 176.3(2) | 174.9(1) | 175.6(2) |
| N2−Co−N5 | 98.1(2) | 99.1(2) | 101.7(1) | 101.7(1) |
| N3−Co−N4 | 97.6(3) | 96.8(2) | 94.9(1) | 94.8(2) |
| N3−Co−N5 | 178.1(3) | 176.9(2) | 156.0(1) | 157.6(1) |
| N4−Co−N5 | 82.4(2) | 82.7(2) | 82.2(1) | 82.5(2) |
| N3−Co−C | 90.2(3) | 88.9(2) | 113.3(1) | 114.5(2) |
| N5−Co−C | 91.8(3) | 88.0(2) | 42.8(1) | 43.4(1) |
| N1−Co−C | 176.3(3) | 177.0(2) | 150.6(1) | 155.2(2) |
| Co−N1−C1 | 117.8(4) | 127.0(4) | 120.2(2) | 128.2(3) |
| Co−N1−C5 | 125.7(5) | 114.4(4) | 122.0(2) | 113.3(3) |
| Co−C−N5 | | | 70.0(2) | 69.1(2) |

[a] Mean values obtained for two crystallographically independent molecules.[5] [b] Mean values obtained for two crystallographically independent molecules.[4] [c] Reference 3.

**X-ray Structure.** An ORTEP view of the complex **2′** showing the formation of the Co−C−N three-membered cycle is reported in Figure 1. The complex **2′** differs from analogous **1′** in having a shorter $-CH_2-$ vs $-CH_2CH_2-$ arm linking the pyridyl group to the equatorial moiety and in the configuration of the C8, C18, N2, and N5 chiral centers. That is, in **2′** both the C*−Me bonds lie in the half-plane containing the three-membered cycle and both the N*−CH₂py bonds lie in the opposite half-plane. In contrast in **1**, the two C*−Me bonds and also the two N*−CH₂py residues lie in opposite half-planes. Selected bond lengths and angles for complexes **1′** and **2′** are reported in Table 1. For a comparison, in Table 1 the parameters for the corresponding methyl derivatives $[MeCo^{III}(L_1NH\text{-}py)(HL_1NH\text{-}py)]^+$ (**1″**) (containing the long $-CH_2CH_2-$ arm) and $[MeCo^{III}(LNH\text{-}py)(HLNH\text{-}py)]^+$ (**2″**) (containing the short $-CH_2-$ arm), are also reported. The coordination polyhedron about Co exhibits distortions from the octahedral geometry, similar to those found in **1** (Table 1). Only the Co−N1 axial distance (2.035(3) Å) is significantly shorter than that of **1** (2.118(3) Å) but is comparable with the mean value found in **2″**. These differences are due to the different constraints required for the five-membered metallacycle closure with to the respect to those required for the six-membered cycle closure in **1**. In fact, also the angles in the five-membered cycle involving the coordinated pyridyl ring are different by about 10° from those reported for **1** (Table 1). In contrast, the distances and

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(4) Dreos, R.; Felluga, A.; Nardin, G.; Randaccio, L.; Sandri, M.; Tauzher, G. *Inorg. Chem.* **2002**, *41*, 4548.

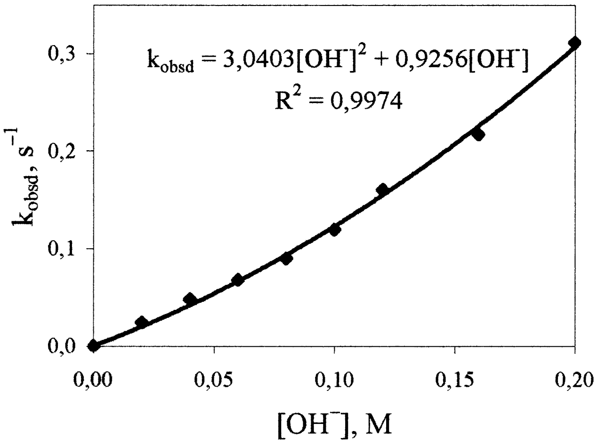
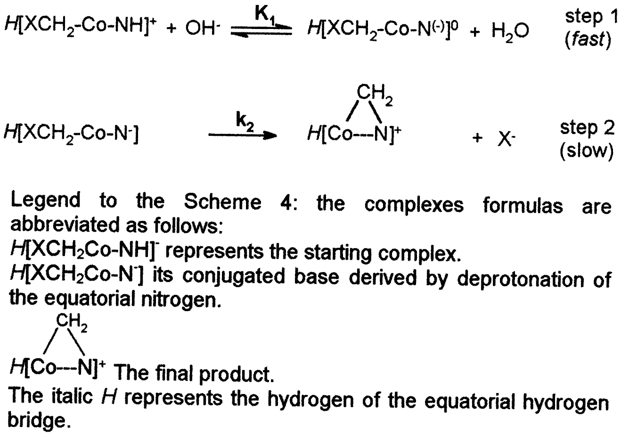


**Figure 2.** Fitting of the $k_{obsd}$ vs $[OH^-]$ values for the cyclization reaction of $[ClCH_2Co^{III}(L_1NH\text{-}py)(HL_1NH\text{-}py)]^+$. Data were collected at 25 °C, and the ionic strength was 0.2 M ($NaClO_4$).

### Scheme 4



Legend to the Scheme 4: the complexes formulas are abbreviated as follows:
*H*[XCH₂Co-NH]⁺ represents the starting complex.
*H*[XCH₂Co-N⁻] its conjugated base derived by deprotonation of the equatorial nitrogen.
*H*[Co---N]⁺ The final product.
The italic *H* represents the hydrogen of the equatorial hydrogen bridge.

angles involving the three-membered cycle are comparable in **2′** and **1**.

**Kinetics and Mechanisms.** The kinetics of metallacycle formation in **2** was followed spectrophotometrically by means a stopped-flow apparatus in alkaline solution. 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 conform to first-order kinetics in complex **2**. Values of $k_{obsd}$ ($s^{-1}$) have been analyzed as a function of $[OH^-]$. The form of $k_{obsd}$ (eq 1

$$k_{obsd} = a[OH^-] + b[OH^-]^2 \tag{1}$$

and Figure 2) was found to be of the same type that as previously reported for the cyclization reaction of complex **1**.[3] Therefore, the same stoichiometric mechanism may be formally assigned in the two cases. However, comparison of Schemes 2 and 3 shows that for the ring closure the inversion of configuration at the equatorial nucleophilic nitrogen is prerequisite in **1**, but not in **2**.

On the basis of the kinetic data it is postulated that in the first step a fast reversible deprotonation of the amine N bearing the pendant pyridyl group occurs. The slow nucleophilic addition of the nitrogen to the axial carbon follows (Scheme 4).

The second order in $[OH^-]$ is consistent with the presence of a further acid−base equilibrium, which could be identified in the reversible deprotonation of the O−H···O bridge. The same kinetic behavior has been observed in complexes of type **1**. No further investigation will be done on this aspect, since our primary interest is concerned with the picture of the transition state of step 2 in Scheme 4.

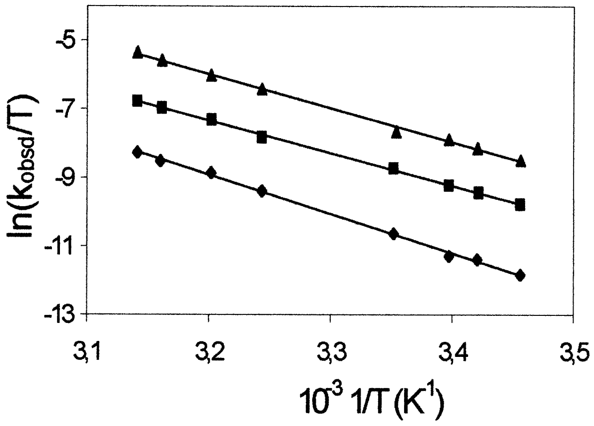


**Figure 3.** Eyring plot for cyclization reactions of complexes of type **1** with X = Cl (◆) and Br (▲) and for complex **2** (■).

**Table 2. Rate Constants at 25 °C and Activation Parameters for the Cyclization Reactions**

| X | $K_1k_2$ ($M^{-1}\ s^{-1}$) | $\Delta H^{\ddagger}_{app}$ (kJ mol$^{-1}$) | $\Delta S^{\ddagger}_{app}$ (J K$^{-1}$ mol$^{-1}$) |
|---|---|---|---|
| | $[XCH_2Co^{III}(LNH\text{-}py)(HLNH\text{-}py)]^+$ | | |
| Cl | 0.17 ± 0.01 | 94.90 ± 1.60 | 31.77 ± 5.32 |
| Br | 2.69 ± 0.28 | 82.38 ± 1.82 | 16.12 ± 5.98 |
| I | 4.93 ± 0.28 | | |
| | $[XCH_2Co^{III}(L_1NH\text{-}py)(HL_1NH\text{-}py)]^+$ | | |
| Cl | 0.92 ± 0.07 | 78.89 ± 1.15 | −6.34 ± 3.82 |

The values of the activation parameters $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ have been determined for the reaction of **1** and **2** (with X = Cl, Br) (Figure 3 and Table 2) by introducing in the Eyring equation (eq 2) the kinetic constants ($k_{obsd} = K_1k_2[OH^-]$) determined at sufficiently low NaOH (0.02 M) concentrations in order to minimize the contribution of the quadratic term in the $k_{obsd}$ equation (1).

$$\ln\frac{k_{obsd}}{T} = \ln\frac{\kappa}{h} - \frac{\Delta H^{\ddagger}_{app}}{RT} + \frac{\Delta S^{\ddagger}_{app}}{R} \tag{2}$$

## Discussion

A rare example[6] of intermolecular nucleophilic substitution at a $-CH_2X$ group linked to a Co is given by the following reaction, which requires drastic experimental conditions:

$$LCo(DH)_2CH_2Br + {}^-OCH_3 \rightarrow LCo(DH)_2CH_2OCH_3 + Br^-$$

In general, it can be said that the halogenoalkyl groups are scarcely reactive. Some observations accumulated in the course of our studies on the alkylcobaloximes clearly indicate that $-CH_2X$ is quite inert toward

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(5) Dreos, R.; Felluga, A.; Nardin, G.; Randaccio, L.; Siega, P.; Tauzher, G. *Eur. J. Inorg. Chem.* **2001**, 267.

(6) Marzilli, L. G.; Bayo, F.; Summers, M. F. Thomas, L. B.; Zangrando, E.; Bresciani-Pahor, N.; Mari, M.; Randaccio, L. *J. Am. Chem. Soc.* **1987**, *109*, 6045.

alkaline hydrolysis.[7] This is also consistent with the observation that the syntheses of halogenoalkyl cobalt complexes are generally performed in basic media and no problems were encountered in obtaining the pure products.[8] There is no evidence for the complexes under investigation of concomitant alkaline hydrolysis of the alkylhalogeno groups, but only the metallacyclic species were obtained in quantitative yields. In contrast with this apparent inertness of the $-CH_2X$ fragment, the cyclization reaction is surprisingly rapid. Therefore, it is of interest to ascertain the factor determining this enhancement in the reaction rate. Kinetic or intramolecular reactions of the cobalt complexes have been rarely reported. In contrast, intramolecular reactivity has been extensively studied in the case of organic substrates. Therefore, there have been several concepts developed by physical organic chemists, which could be transferred to the organometallic compounds. To apply this approach, the following points are examined.

**Bromide:Chloride Ratios.** The difference in reactivity between bromides and chlorides in both the intermolecular and intramolecular displacement reactions has been regarded as an index of the degree of bond extension to the leaving group and, hence, as an index of the degree of bond formation to the entering group in the transition state.[9] The dominant factor, which favors bromide over chloride, was identified in the bond dissociation energy difference.[10a] Bromide: chloride rate constant ratios in the intramolecular reactions for three-membered-ring systems generally fall in the range 35−80. These values are consistent with partial cleavage of the C−X bond (or a partial C-entering group formation) in the transition state.[9c]

For the three-membered-ring formation in **2**, the bromide:chloride ratio was found to be equal to 16. Although this value is lower as compared with those mentioned above, it could suggest a partial $CH_2-N$ bond formation in the transition state, i.e., an incipient formation of the metallacycle.

The energies required for the C−Cl and C−Br bond dissociations are reflected also by the $\Delta H^{\ddagger}$ values associated with the cyclization reactions of the $ClCH_2$ and $BrCH_2$ derivatives, these values being 94.90 ± 1.6 and 82.38 ± 1.8 kJ $mol^{-1}$, respectively (Table 2).

**Proximity Effect.** The proximity of the two reactive centers plays a fundamental role in the kinetic process. Menger's "*spatiotemporal hypothesis*"[10] postulates that "the rate of reaction between two functionalities is proportional to the time that these functionalities reside within a critical distance". On the basis of statistical treatments, it has been suggested[11a] that a reaction takes place when the separation between functional groups becomes shorter than a given distance. Good fits between experimental and calculated cyclization constants were obtained with a distance equal to 2.3−2.7 Å. Since this value is less than the diameter of a water molecule, the nucleophile and electrophile must desolvate while forming a reactive complex. It has been suggested that the energy necessary to reorganize solvent molecules around reacting species comprises almost all the activation energy of some reactions. If a rigid covalent framework holds the two functionalities within the critical distances (time is not a factor in this case because of the rigidity of the system), very high reaction rates can be expected. There is no doubt that in complexes **1** and **2** the reactive centers are situated within a distance very close to the critical distance and that no desolvation energy is necessary to the ring closure process. Strictly speaking, the distance interposed between the equatorial N and the target carbon in **1** and **2** are not available, but it is reasonable to assign to these distances values very close to those found in the corresponding Me derivatives **1″** and **2″**, which are 2.8611 and 2.8052 Å, respectively. A very short distance between these functionalities is expected to be present also in solution, in accord with the high reaction rates.

This situation can be compared with that occurring in the enzyme reaction, where the function of the enzyme is to hold the substrate within the critical distance of the catalytic group.

It is also remarkable that the Co−N(equatorial) bond is still more shortened when the strong nucleophilic $N^-$ is formed, and this further contributes to approach of the reactive sites.

**Orientation Effect.** The idea that the rate enhancement may be greatly affected by the angle of approach[11] of the two reacting sites has been criticized on the basis of experimental studies. These studies tend to demonstrate the existence of considerable flexibility in the approach of the two reagents.[12]

It is apparent that in complexes **1** and **2** the critical distances between the reactant sites is quite favorable, but at the same time the angle of approach does not allow a favorable juxtaposition of the reactants. In fact, for the metallacycle formation a considerable bending of the Co−C bond over the plane of the equatorial ligand is required, the C−Co−N angle of 90° in **1** being reduced to 40° in **1′** and likewise on passing from **2** to **2′**. As suggested above, the value of the bromide:chloride ratio (see above) suggests a partial formation of the metallacycle in the transition state. We believe that the conformational changes involved in this process can be associated with relatively high activation energy.

**Entropy Effect.** According to the mechanism, the overall rate constant is equal to $K_1k_2$, where $K_1$ is the equilibrium constant for step 1 and $k_2$ is the rate constant for step 2 (Scheme 4), which is the slow step. The overall entropy[13] of activation ($\Delta S^{\ddagger}_{app}$) is therefore equal to $\Delta S_1 + \Delta S^{\ddagger}_2$, where $\Delta S_1$ is the entropy change for the preequilibrium and $\Delta S^{\ddagger}_2$ is the entropy of activation for step 2 (Scheme 4). Data in Table 2 show that for complexes of type **1** the overall entropy changes are fairly large and positive, and they are close to zero

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[7] Dreos Garlatti, R.; Tauzher, G.; Costa, G. *Inorg. Chim. Acta* **1983**, *71*, 9.

[8] Gupta, B. D.; Roy, S. *Inorg. Chim. Acta* **1988**, *146*, 209.

[9] (a) Modena, G. *Acc. Chem. Res.* **1771**, *4*, 73 and references therein. (b) Hoffman, H. M. R. *J. Chem. Soc.* **1965**, 6753. (c) Bird, R.; Stirling, C. G. M. *J. Chem. Soc., Perkin Trans. 2* **1973**, 1221. (d) Bird, R.; Knipe, A. C.; Stirling, C. G. M. *J. Chem. Soc., Perkin Trans. 2* **1973**, 1215.

[10] (a) Menger, F. M. *Acc. Chem. Res.* **1985**, *18*, 128. (b) Menger, F. M. In *Nucleophilicity*; Adv. Chem. Ser. 215; Harris, G. M., McManus, S. P., Eds.; American Chemical Society: Washington, DC, 1987; Chapter 14.

[11] (a) Sisido, M. *Macromolecules* **1971**, *4*, 737. (b) Storm, D. R.; Koshland, D. E., Jr. *J. Am. Chem. Soc.* **1972**, *94*, 5805.

[12] (a) Dafforn, A.; Koshland, D. E., Jr. *Biochem. Biophys. Res. Commun.* **1973**, *52*, 779. (b) Menger, F. M. *Tetrahedron* **1983**, *39*, 1013.

[13] Perlmutter-Hayman, B. *Prog. Inorg. Chem.* **1973**, *20*, 229.

for complex **2**. The overall $\Delta S^{\ddagger}_{app}$ values can be thought to derive from a positive contribution of $\Delta S_1$ and a slightly negative contribution of $\Delta S^{\ddagger}_2$. In fact, in pre-equilibrium step 1 (Scheme 4) the two negatively charged reactants (complex and $OH^-$) are more solvated than the products, thus giving a positive value for $\Delta S_{1.}$ The contribution due to the $\Delta S_2{}^{\ddagger}$ term can be also estimated. In accord with the hypothesis of Page and Jencks,[14] when two reacting groups are brought together, as in complexes **1** and **2**, the translational and rotational motions are constrained. Under these conditions an increase in probability that the reaction takes place is expected. In other words, the loss in entropy on going from the ground state to the transition state is smaller than that required in a process in which the same functionalities are part of different molecules.

In conclusion, it can be said that the high specific rate for the metallacycle in these complexes can be explained in terms of positive contributions of the activation entropy and proximity effect, whereas the orientation effect is less favorable.

**Differences in Reactivity between 1 and 2.** Data in Table 2 show that the reaction of **2** is, to a moderate extent, faster than the reaction of **1**. An exhaustive explanation of this difference in the rate constants should be given on the basis of detailed structural features of **1** and **2**. Unfortunately, direct evidence on the structure of **1** and **2** could be not obtained.[15] However, the structures of the related methyl derivatives **1″** and **2″** (Table 1) have been determined and it can be reasonably assumed that certain differences in their geometry could be found also in the respective $ClCH_2$ derivatives. Data in Table 1 show that the N5−Co−C angle is smaller in **2″** (88.0°) than in **1″** (91.8°). An analogous difference in the N5−Co−C angles of the $ClCH_2$ derivative may account for the observed enhancement in the rate constant of **1** with respect to that of **2**, as a consequence of the proximity effect and orientation effect. Data in Table 1 show also that the Co−N(ax) distance is longer in **1″**, having a longer $-CH_2CH_2-$ arm (2.160(5) Å) than in **2″** with the shorter $-CH_2-$ arm (2.032(5) Å). Again we suppose that in the $CH_2Cl$ derivatives a parallel trend may be found. Kinetic data indicate that these differences in Co−N(ax) distances slightly influence the reactivity of the $CH_2Cl$ group situated in a trans position.

Studies concerning the trans effect and trans influence in alkylcobaloximes, the so-called vitamin $B_{12}$ models, have received much attention over the last few years. It was found that rates of axial substitution in the position trans with respect to the alkyl group are largely affected by the nature of the alkyl group.[16] However, the kinetic effect of the neutral axial base on the alkyl group is more difficult to evaluate and only structural data are available. These data indicate that the Co−C bond is scarcely influenced by the nature of the neutral trans base. We have found that in the complexes examined here, the Co−N bond length in the trans position does not significantly affect either the Co−C bond distances or the reactivity of the $CH_2Cl$ group.

## Experimental Section

**Instruments and Materials.** NMR spectra were recorded with a JEOL EX-400 spectrometer ($^1H$ at 400 MHz) from DMSO-$d_6$ solutions with TMS as internal standard. UV/vis spectra were measured with a Perkin-Elmer Lambda 5 spectrophotometer, and kinetics with 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!*

**[$XCH_2Co^{III}$(LNH-py)(HLNH-py)]$ClO_4$ (1; X = Cl, Br, I) and [$\overline{CH_2Co^{III}\text{(LNH-py)(HLN}}$-py)]$ClO_4$ (1′).** Synthesis details and characterization data for these complexes have been reported elsewhere.[3]

**[$ClCH_2Co^{III}$($L_1$NH-py)($HL_1$NH-py)]$ClO_4$** (**2**). This complex was obtained by applying the method used in the synthesis of the corresponding methyl derivative [$MeCo^{III}$($L_1$NH-py)($HL_1$-NH-py)]$ClO_4$ (isomer a) previously reported.[4] In the synthesis $ClCH_2Br$ is used instead of MeI: yellow needles. Anal. Calcd for $C_{21}H_{31}Cl_2CoN_6O_6$: C, 42.51; H, 5.27; N, 14.16. Found: C, 42.10; H, 5.24; N, 13.80. $^1H$ NMR (DMSO-$d_6$): $\delta$ 0.45 (3H, d, $CH_3$); 1.40 (3H, d, $CH_3$); 1.70 (3H, s, $CH_3$); 1.95 (3H, s, $CH_3$); 3.35−3.38 (2H, m, 2CH); 4.30 (2H, m, $CH_2$); 4.45 (2H, dd, $CH_2$); 5.10 (2H, dd, $CH_2Cl$); 5.20 (1H, s, NH); 5.75 (1H, s, NH); 7.35, 7.45, 7.75, 7.90, 8.20, 8.45, 8.55 (8H, $2C_5H_4N$).

**[$\overline{CH_2Co^{III}(L_1\text{NH-py)(H}L_1\text{N}}$-py)]$ClO_4$ (2′).** To a methanol solution (20 mL) of **2** (0.2 g, 0.33 mmol) was added a 0.1 M NaOH aqueous solution (5 mL) at room temperature. After 1 h the methanol was removed by a rotary evaporator at 40 °C. The aqueous solution was allowed to stand overnight. Crystals of the product that formed were recovered by filtration and air-dried. Yield: 95%. Anal. Calcd for $C_{21}H_{30}ClCoN_6O_6$: C, 45.29; H, 5.43; N, 15.09. Found: C, 45.12; H, 5.31; N, 14.89. $^1H$ NMR (DMSO-$d_6$): $\delta$ 1.32 (3H, d, $CH_3$); 1.38 (3H, d, $CH_3$); 1.78 (3H, s, $CH_3$); 1.81 (3H, s, $CH_3$); 3.30−3.75 (2H, m, 2CH); 3.95, 4.02, 4.10, 4.24, 4.45 (6H, $3CH_2$); 5.20 (1H, s, NH); 5.75 (1H, s, NH); 7.15, 7.40, 7.61, 7.71, 7.83, 8.05, 8.45 (8H, $2C_5H_4N$).

**Kinetic Experiments.** The kinetics of metallacycle formation starting from **2** were monitored spectrophotometrically at 400 nm by means of a stopped-flow apparatus at a temperature of 25 ± 0.2 °C. Each reaction was studied with a pseudo-first-order excess of [$OH^-$]. The initial concentration of the complex was $0.5 \times 10^{-3}$ M with a variation of [$OH^-$] from 0.02 to 0.2 M. The ionic strength was adjusted to 0.2 M by $NaClO_4$. 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 $A_t$

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(14) (a) Page, M. I.; Jencks, W. P. *Proc. Natl. Acad. Sci. U.S.A.* **1971**, *68*, 1678. (b) Jencks, W. P.; Page, M. I. *Biochem. Biophys. Res. Commun.* **1974**, *57*, 887.

(15) Attempts to obtaining high-quality crystals for X-ray analysis for $ClCH_2$ derivatives resulted unsuccessful. This is due to the tendency of these complexes to undergo intramolecular cyclization, when left for a long time in solution.

(16) (a) Crumbliss, A. L.; Wilmarth, W. K. *J. Am. Chem. Soc.* **1970**, *92*, 2593. (b) Brown, K. L.; Lyles, D.; Pencovici, N.; Kallen, R. G. *J. Am. Chem. Soc.* **1975**, *97*, 7338. (c) Brown, K. L.; Awtrey, A. W. *Inorg. Chem.* **1978**, *17*, 111. (d) Dreos Garlatti, R.; Tauzher, G.; Costa, G. *Inorg. Chim. Acta* **1983**, *71*, 9. (e) Dreos Garlatti, R.; Tauzher, G.; Costa, G. *Inorg. Chim. Acta* **1983**, *70*, 83. (f) Dreos Garlatti, R.; Tauzher, G.; Costa, G. *Inorg. Chim. Acta* **1986**, *121*, 27. (g) Dreos Garlatti, R.; Tauzher, G.; Costa, G. *Inorg. Chim. Acta* **1981**, *50*, 95. (h) Dreos Garlatti, R.; Tauzher, G.; Costa, G. *Inorg. Chim. Acta* **1984**, *82*, 197. (i) Dücker-Benfer, C.; Dreos, R.; van Eldik, R. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2245. (j) Brasch, N.; Hamza, M. S. A.; van Eldik, R. *Inorg. Chem.* **1997**, *36*, 3216. (k) Hamza, M. S. A.; Zou, X.; Brown, K. L.; van Eldik, R. *Inorg. Chem.* **2001**, *40*, 5440. (l) Hamza, M. S. A.; van Eldik, R.; Pratt, J. M.; Harper, P. L. S.; Betterton, E. A. *Eur. J. Inorg. Chem.* **2002**, 580.

$= A_\infty + (A_0 - A_\infty)\exp(-k_{obsd}t)$, which all runs follow exactly. Values of $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ were calculated from the slopes and intercepts, respectively, of plots of $\ln(k_{obsd}/T)$ versus $1/T$. The $k_{obsd}$ values were determined as above at a constant concentration of $OH^-$ (0.02 M) and in the temperature range 16.2−45.2 °C.

**Structure Determination.** Single crystals, suitable for X-ray data collection of **2**, were obtained as reported in the syntheses. X-ray diffraction data were collected at room temperature with a Nonius DIP1030 H system using graphite-monochromated Mo Kα radiation ($\lambda = 0.710\ 73$ Å). A total of 45 frames were collected, using the Xpress program,[17] over half of the reciprocal space with rotation of 4° about the $\varphi$ 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.[18] 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.[19] A suite of programs[20] was also used in the geometrical and final calculation. Table 3 reports a summary of data collection procedures and crystallographic statistics.

**Table 3. Crystallographic Data for 2′**

| | |
|---|---|
| empirical formula | $C_{21}H_{30}ClCoN_6O_6$ |
| fw | 556.89 |
| temp, K | 293(2) |
| wavelength, Å | 0.71073 Å |
| cryst syst, space group | orthorhombic, *Pcan* |
| unit cell dimens | |
| *a*, Å | 10.840(3) |
| *b*, Å | 14.930(1) |
| *c*, Å | 31.751(4) |
| *V*, Å$^3$ | 5138.6(2) |
| *Z* | 8 |
| calcd density, Mg/m$^3$ | 1.440 |
| abs coeff, mm$^{-1}$ | 0.819 |
| final *R* indices ($I > 2\sigma(I)$) | $R_1 = 0.0557$, $wR2 = 0.1667$ |
| *R* indices (all data) | $R1 = 0.0850$, $wR2 = 0.2069$ |

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**Supporting Information Available:** X-ray crystallographic file, in CIF format, for complex **2′**. This material is available free of charge via the Internet at http://pubs.acs.org.

OM030024P

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[17] Schierbeek, B. Nonius, Delft, The Netherlands, 1998.

[18] (a) Collaborative Computational Project, Number 4. *Acta Crystallogr., Sect. D* **1994**, *D50*, 760. (b) Sheldrick, G. M. SHELXS-86, Program for Structure Solution. *Acta Crystallogr., Sect. A* **1990**, *A46*, 467.

[19] Sheldrick, G. M. SHELXL-93, Program for Structure Refinement; Universität Göttingen, Göttingen, Germany, 1993.

[20] Farrugia, L. *J. Appl. Crystallogr.* **1999**, *32*, 837.