The Reduction of Cyanopyridine Complexes of Pentaamminecobalt(III) by Chromium(II). Orbital Paths for Reduction of the Linkage Isomers of 4-Cyanopyridine

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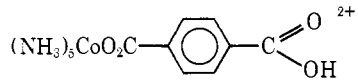
Abstract: The chromium(II) reduction of the pentaamminecobalt(III) complexes with 2-, 3-, and 4-cyanopyridine coordinated through the nitrile nitrogen and with 4-cyanopyridine coordinated through the pyridine nitrogen have been studied. All reductions were shown to occur via an inner-sphere mechanism by product analysis. The reductions of the nitrile-bonded complexes were inversely dependent on the hydrogen ion concentration indicating the rapid preequilibria, $(NH_3)_5CoNC\text{-}pyH^{4+} \rightleftarrows (NH_3)_5CoNCpy^{3+} + H^+$, with reduction of protonated and unprotonated species occurring at different rates. The rates of reduction and activation parameters for the deprotonated forms of the 3- and 4-cyanopyridine complexes are 2.67 and 6370 M^{-1} sec^{-1} at 25° and μ = 1.0 M ($LiClO_4$) with $\Delta H^{\ddagger}$ = 7.6 ± 0.6 and 0.3 ± 0.3 kcal mol^{-1} and $\Delta S^{\ddagger}$ = −31 ± 4 and −40 ± 4 eu, respectively. A lower limit for reduction of the 2-cyanopyridine complex was established as 1.6×10^4 M^{-1} sec^{-1} at 25° and μ = 1.0 M ($LiClO_4$). Reduction of the complex with 4-cyanopyridine coordinated through the pyridine nitrogen was independent of the hydrogen ion concentration with rate constant 124 M^{-1} sec^{-1} at 25° and μ = 1.0 M ($LiClO_4$) and $\Delta H^{\ddagger}$ = 0.2 ± 0.3 kcal mol^{-1} and $\Delta S^{\ddagger}$ = −48 ± 4 eu. In this study, an intermediate was formed by initial attack of chromium(II) at the uncoordinated nitrile nitrogen to give $(OH_2)_5Cr(NCpy)^{3+}$. This intermediate was reduced by excess chromium(II) with a rate constant of 7100 M^{-1} sec^{-1} at 25°. The results are discussed in terms of the "reducibility" of the ligands and shown to be consistent with a radical-ion mechanism. A detailed orbital electron transfer path is proposed for the 4-cyanopyridine system.

Introduction

Many factors have been found to affect the rates and mechanism of inner-sphere electron transfer reactions.[1] These reactions appear to depend upon the presence of suitable polar groups on the bridging ligand and their relationship to the energy and symmetry of the orbitals on the rest of the mediating ligand. For example, the chromium(II) reduction of **1**[2] and **2**[3] proceeds according to different rate



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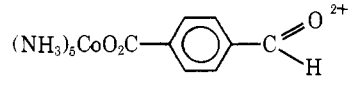

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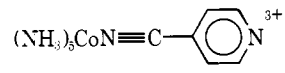
laws and different overall mechanisms. For the latter complex, the interpretation is complicated by the observation of a first-order hydrogen ion term in the rate law. However, it was shown that attack of reductant took place at the remote formyl group, and a radical-ion mechanism was postulated. For substituted pyridines and benzonitriles where the ligands are coordinated to the oxidant via the pyridine N and nitrile N, respectively, no hydrogen ion dependence is observed.[4] Remote attack has also been observed for the reduction of isonicotinamidopentaamminecobalt(III) by chromium(II) and a radical-ion mechanism postulated.[5]

For the above reductions, contributions to the mechanism and rate are probably made by the nature of the bridging group, the energy of the lowest empty antibonding orbitals, and the "reducibility" of the bridging ligand. Depending upon the relative contributions of the preceding, the mechanism could be inner- or outer-sphere, radical-ion, super exchange, or resonance transfer. No attempt has been made to systematically evaluate each effect and determine its contribution to the overall mechanism. We have studied the chromium(II) reductions of nitrile-bonded complexes of 2-, 3-, and 4-cyanopyridine with $(NH_3)_5Co^{3+}$ in an attempt to determine the effect of a change in reducibility on the electron transfer process. Also, we have studied the reduction of the pyridine-bonded complex in the case of 4-cyanopyridine. For the linkage isomers I and II, the reducibility of



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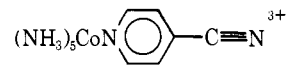


II

the ligand is approximately constant as is the energy of the lowest empty antibonding orbitals. This may then allow us to determine the efficiency of pyridine N as opposed to nitrile nitrogen as a binding group for the reductant. Consideration of the symmetry of the orbitals involved in bridging and the relationship of these orbitals to orbitals on the rest of the ligand may yield information on the path of electron transfer.

Experimental Section

Solutions for kinetic studies were prepared from water doubly distilled from an all-glass apparatus. Standard solutions of lithium perchlorate and perchloric acid were prepared as described previously.[6] Chromium(II) perchlorate was prepared by reducing chromium(III) perchlorate with zinc amalgam and also by dissolving high-purity chromium metal in perchloric acid. All solutions were handled using standard syringe techniques under an argon atmosphere.

The complexes were prepared and purified as described previously.[7]

Ion-Exchange Separation of Reaction Mixtures. Chromatographic separations were carried out using Dowex 50W-X2 in the lithium ion form in a cold room maintained at 1°. Elution was carried out initially with a solution 0.25 M in $NaClO_4$ and 0.05 M in $HClO_4$ to remove Co^{2+} and effect separation of the Cr^{3+} species. The concentration of $NaClO_4$ was increased when the product band was eluted. Chromium concentrations were determined spectrophotometrically as chromate, ϵ 4815 M^{-1} cm^{-1} at 372 nm.

Kinetic Measurements. The rates of reduction were followed using a Durrum stopped-flow spectrophotometer and a Beckman Acta CIII spectrophotometer. Absorbance changes were followed at 470, 550, and 285 nm. All reactions were carried out under pseudo-first-order conditions (reductant in a 10–20-fold excess over oxidant). The observed rate constant was obtained from plots of log $(A_t - A_\infty)$ vs. time, where A_t and A_∞ are the absorbances at time t and after the reaction was complete. The temperature-control equipment has been described previously.[8]

For reduction of the pyridine-bonded 4-cyanopyridine complex, an intermediate was observed at 285 nm, and the kinetic data were treated according to two consecutive reactions

$$A \xrightarrow{k_1} B \xrightarrow{k_2} C \qquad (1)$$

in a manner similar to that reported by Nordmeyer.[5]

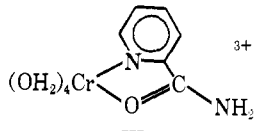
Physical Measurements. Electronic spectra were obtained using a Beckman Acta CIII spectrophotometer.

Results

Characterization of the complexes has previously been reported.[7] The form of the rate laws for reduction of the linkage isomers of 4-cyanopyridine also provides support for the previous assignments. The reduction of II is independent of hydrogen ion concentration, whereas the complex coordinated through the nitrile nitrogen has an inverse hydrogen ion term in the rate law. For the latter complex, protonation can occur at the uncoordinated pyridine nitrogen, thus leading to the observed rate law. For II, protonation at the uncoordinated nitrile is unlikely.

Stoichiometry and Product Analysis. The stoichiometry of the reduction of the complexes was determined by analysis for Co(II) produced from reaction mixtures in which the Co(III) complex was in excess with respect to the reductant.[9] In all cases, 1 mol of cobalt(III) complex was consumed per mole of chromium(II).

The stoichiometry and nature of the products of reduction were also investigated by submitting reaction mixtures to cation exchange chromatography on Dowex 50WX-2 in the lithium ion form. By collecting the total Cr(III) products, all reactions were shown to take place by reaction of one cobalt(III) to one chromium(II). In addition to varying amounts of $Cr(OH_2)_6^{3+}$, all three reactions gave products which contained the organic ligand or some form of it. From reduction of the 2-cyanopyridine complex, a pink product was obtained that moved down the column as a 3+. The visible spectrum of this Cr(III) product was identical with that observed from the reduction of 2-carboxamidopyridinopentaamminecobalt(III). Therefore the product is formulated as the chelate III. Attempts to determine the



III

percent ligand transferred were made by isolating all of the chelate. Removal from the column was difficult and only about 75% of the product could be recovered.

The reduction of the 3-cyanopyridine complex yielded a pink-purple Cr(III) complex which eluted as a 3+. The visible spectrum had maxima (extinction coefficient) at 556 (19.2) and 400 nm (20.4 M^{-1} cm^{-1}). This product is formulated as the pyridine-bonded complex **3**

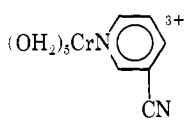


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Table I. Percent Ligand Transfer in Reduction of II by Cr^{2+}[a]

Co^{3+}, mmol	Cr^{2+}, mmol	$[H^+]$	[4] (found)	% ligand transfer
0.220	0.220	0.095	0.203	92
0.254	0.220	0.095	0.210	96
0.219	0.220	0.795	0.203	93
0.182	0.220	0.095	0.170	93
0.202	0.198	0.156	0.187	96

[a] $T = 25°C$.

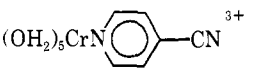
Table II. Kinetic Data for the Reduction of 2-Cyanopyridinopentaamminecobalt(III) by Chromium(II)[a]

$10^4 \times$ [Co(III)], M	$10^3 \times$ [Cr(II)], M	$[H^+]$, M	k_{obsd}, M^{-1} sec^{-1} [b]
8.5	10.9	0.751	246[c]
4.8	22.5	0.398	467
5.4	22.5	0.206	850
9.8	11.3	0.206	875
9.0	10.9	0.101	1720[c]
5.8	113	0.103	1710
5.2	11.3	0.080	2100
5.1	11.3	0.048	3400
3.0	11.3	0.032	4900
3.0	11.3	0.032	4600

[a] $T = 25.1°C$; ionic strength is 1.0 M $LiClO_4$; λ 285 nm. [b] Each rate constant is the average of three runs and is accurate to within 6%. [c] λ 471 nm.

The spectrum obtained is in good agreement with that of Bakac, Marcec, and Orhanovic[10] who give λ_{max} (ϵ_{max}) of 561 (19.0) and 402 nm (20.5 M^{-1} cm^{-1}). Only 55% ligand transfer was observed in this case.

For reduction of nitrile-bonded 4-cyanopyridine, the Cr(III) product obtained is formulated as **4**



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with λ_{max} (ϵ_{max}) at 555 (19.5) and 400 nm (21.8 M^{-1} cm^{-1}). Approximately 60–70% ligand transfer was observed. For reduction of the pyridine-bonded linkage isomer, an identical product was obtained with λ_{max} (ϵ_{max}) at 555 (19.4) and 400 nm (21.2 M^{-1} cm^{-1}). The percent ligand transfer was investigated under a variety of conditions for this complex, and the results are shown in Table I. It appears then that reduction of both linkage isomers gives the same product.

In all cases, the nitrile-coordinated complexes gave less than 100% ligand transfer experimentally. This could be due to a possible outer-sphere path for reduction. It should also be noted that the nitrile-bonded complexes are susceptible to hydrolysis of the coordinated nitrile group[7,11] under the conditions used for the product studies. This would lead to a decreased amount of Cr(III)-cyanopyridine complex. This is not a problem for the 4-cyanopyridine complex coordinated through the pyridine nitrogen.

Kinetic Studies. 2-Cyanopyridine Complex. The reaction of the 2-cyanopyridine complex with chromium(II) was first order in both chromium(II) and cobalt(III) complex and inversely dependent on the hydrogen ion concentration. The data are consistent with a rate law of the form

$$-\frac{d \ln [\text{Co(III) complex}]}{dt} = \frac{k[Cr^{2+}]}{[H^+]} = k_{obsd}[Cr^{2+}] \qquad (2)$$

The kinetic parameters are given in Table II. A plot of k_{obsd}

Table III. Kinetic Data for the Reduction of 3-Cyanopyridinopentaamminecobalt(III) by Chromium(II)[a]

T, °C	$10^3 \times$ [Co(III)], M	$10^2 \times$ [Cr(II)], M	$[H^+]$, M	k_{obsd}, M^{-1} sec^{-1} [b]
9.2	1.1	3.0	0.851	0.180
	1.2	3.0	0.448	0.280
	1.2	3.0	0.224	0.400
	1.1	3.0	0.112	0.630
	1.1	3.0	0.067	0.720
	1.2	3.0	0.045	0.860
16.0	1.1	3.0	0.858	0.270
	1.1	3.0	0.455	0.370
	1.1	3.0	0.231	0.610
	1.1	3.0	0.119	0.860
	1.1	3.0	0.074	1.05
	1.1	3.0	0.052	1.16
25.4	2.3	2.4	0.910	0.43[d]
	1.1	1.2	0.900	0.42
	1.1	1.2	0.900	0.44
	1.3	1.2	0.498	0.56
	1.3	2.4	0.504	0.57
	1.1	1.2	0.319	0.77
	1.2	1.2	0.207	0.99
	1.1	1.2	0.140	1.23
	1.1	1.2	0.117	1.38
	1.1	1.2	0.117	1.34
	2.0	11.3	0.096	1.61[c]
	0.5	4.7	0.096	1.55[c]
	1.7	7.9	0.064	1.75[c]
	1.6	5.6	0.046	1.90[c]
34.0	1.1	1.5	0.924	0.640
	1.1	1.5	0.454	1.00
	1.0	3.0	0.460	0.920
	1.0	1.5	0.230	1.44
	1.0	1.5	0.118	1.93
34.0	1.0	1.5	0.073	2.37
	1.0	1.5	0.063	2.48
	1.5	6.5	0.063	2.42[c]

[a] Ionic strength is 1.0 M with $LiClO_4$; λ 470 nm. [b] Each rate constant is accurate to within 5%. [c] Stopped-flow determination. [d] λ 555 nm.

vs. $[H^+]^{-1}$ is linear with an intercept of approximately zero as required by (2). The data points at $[H^+] = 0.032$ begin to deviate from (2), but hydrolysis of the nitrile to the carboxamide make these determinations suspect.

A mechanism consistent with the rate law is

$$(NH_3)_5CoN{\equiv}C\text{-}(C_5H_4N)^{4+} \overset{K_a}{\rightleftharpoons} (NH_3)_5CoN{\equiv}C\text{-}(C_5H_4N)^{3+} + H^+ \quad (3)$$

$$(NH_3)_5CoN{\equiv}C\text{-}(C_5H_4N)^{3+} + Cr^{2+} \xrightarrow{k'} \text{products} \quad (4)$$

The above gives $k_{obsd} = k'K_a/(K_a + [H^+])$. Since $K_a \ll [H^+]$, $k_{obsd} = k'K_a/[H^+]$. The slope of the plot of k_{obsd} vs. $[H^+]^{-1}$ is 164 ± 6 sec^{-1}. One can estimate that $K_a \leq 0.01$ M in order to obtain a straight line and thus $k' \leq 1.6 \times 10^4$ M^{-1} sec^{-1}. This is reasonable in light of the rate of reduction obtained for the 2-carboxamidopyridino complex of $(NH_3)_5Co^{3+}$.[8]

The nature of the "products" in eq 4 was unexpected. The expected product for this reaction (inner-sphere since a Cr(III) product other than $Cr(OH_2)_6^{3+}$ was isolated) was the $(OH_2)_5Cr^{3+}$ complex with 2-cyanopyridine coordinated via the pyridine nitrogen. However, the observed product was the chelate III. Since hydrolysis of the coordinated ligand must have occurred after the initial electron transfer, the following scheme seems reasonable.

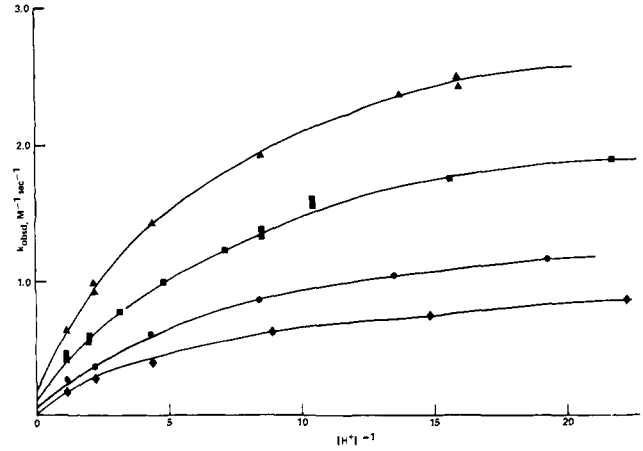

Figure 1. Plots of k_{obsd} vs. $[H^+]^{-1}$ for reduction of nitrile-bonded 3-cyanopyridinopentaamminecobalt(III) by chromium(II) at 9.2°, 16.0°, 25.4°, 34.0°.

$$(NH_3)_5CoN{\equiv}C\text{-}(C_5H_4N)^{3+} + Cr^{2+} \xrightarrow{k'} (OH_2)_5CrN{\equiv}C\text{-}(C_5H_4N)^{3+} + Co^{2+} \quad (5)$$

$$(OH_2)_4Cr(OCH{=}CHN)^{3+} \longrightarrow (OH_2)_4Cr(O{=}C\text{-}CH_2\text{-}NH_2)^{3+} \quad (6)$$

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Evidence for the hydrolysis was obtained by studying the reduction at 400 nm. The stopped-flow traces showed an initial increase in absorbance due to production of the monodentate 2-cyanopyridine complex. This absorbance increase corresponded to the rate of reduction (obtained at 285 and 471 nm). The initial increase was followed by a slower ($t_{1/2} \sim 1$ min) further increase in absorbance which may correspond to formation of the chelate III. The absorbance changes are consistent with the known extinction coefficient of III (ϵ_{400} 44.9 M^{-1} cm^{-1}) and that of other monodentate complexes of $(OH_2)_5Cr^{3+}$ coordinated through the pyridine nitrogen ($\epsilon_{400} \sim 21$ M^{-1} cm^{-1}).[5]

3-Cyanopyridine Complex. The reduction of the 3-cyanopyridine complex was also inversely dependent on the hydrogen ion concentration and follows the rate law

$$-\frac{d \ln [\text{Co(III) complex}]}{dt} = \frac{a[H^+] + b[Cr^{2+}]}{c + [H^+]} = k_{obsd}[Cr^{2+}] \quad (7)$$

The rate data are given in Table III, and plots of k_{obsd} vs. $[H^+]^{-1}$ at various temperatures are given in Figure 1. A mechanism consistent with the rate law is

$$(NH_3)_5CoN{\equiv}C\text{-}(C_5H_4N)^{4+} \rightleftharpoons (NH_3)_5CoN{\equiv}C\text{-}(C_5H_4N)^{3+} + H^+ \quad (8)$$

$$(NH_3)_5CoN{\equiv}C\text{-}(C_5H_4N)^{4+} + Cr^{2+} \xrightarrow{k_1} \text{products} \quad (9)$$

$$(NH_3)_5CoN{\equiv}C\text{-}(C_5H_4N)^{3+} + Cr^{2+} \xrightarrow{k_2} \text{products} \quad (10)$$

Table IV. Kinetic Data for the Reduction of Nitrile- and Pyridine-Bonded 4-Cyanopyridine Complexes of Pentaamminecobalt(III) by Chromium(II)[a, b]

T, °C	$10^4 \times$ [Co(III)], M	$10^2 \times$ [Cr(II)], M	[H+], M	k, M^{-1} sec^{-1}
	$(NH_3)_5CoN$⟨◯⟩$-C\equiv N^{3+}$			
25.1	14	1.96	0.213	124
	26	3.92	0.213	125
	20	1.96	0.744	123
	24	2.25	0.499	124
34.6	28	2.25	0.175	129
	25	4.50	0.175	130
43.3	28	2.25	0.175	135
	20	4.50	0.175	136
	$(NH_3)_5CoN\equiv C-$⟨◯⟩N^{3+}			
				k_{obsd}, M^{-1} sec^{-1}
25.0	5.6	2.25	0.795	350
	7.0	2.20	0.403	650
	4.3	2.25	0.214	1240
	6.0	4.50	0.214	1140
	4.0	2.25	0.115	1880
	6.8	2.25	0.080	2400
	4.5	2.25	0.049	3160
34.4	5.7	2.25	0.400	770
	6.6	2.25	0.206	1310
	3.3	2.21	0.203	1300
	7.0	2.25	0.115	2160
	3.3	2.21	0.110	2000
	3.9	2.21	0.082	2500
	3.9	2.21	0.059	3100
43.4	3.8	2.30	0.395	835
	6.9	2.21	0.206	1370
	5.0	2.21	0.110	2300
	3.6	2.30	0.110	2350
	3.6	2.21	0.083	2750
	5.0	2.21	0.059	3300

[a] Ionic strength is 1.0 M with $LiClO_4$. [b] Rate constants are averages of at least three separate determinations. [c] Data obtained predominantly at 470 nm. [d] Data obtained at 285 nm.

The rate law derived for the above gives

$$k_{obsd} = \frac{k_1[H^+] + k_2K_a}{K_a + [H^+]} \quad (11)$$

which has the same form as eq 7. The full lines in Figure 1 represent a nonlinear least-squares fit of the experimental data points to an equation of the form in (7). The values obtained for K_a varied little with temperature and a value of $K_a = 0.10 \pm 0.02$ M is given. At 9.2, 16.0, 25.4, and 34.0°C the values of k_2 obtained were 1.20, 1.65, 2.67, and 3.85 M^{-1} sec^{-1}, respectively. These values gave $\Delta H_2^{\ddagger} = 7.6 \pm 0.6$ kcal mol^{-1} and $\Delta S_2^{\ddagger} = -31 \pm 4$ eu. The values of k_1 were small (less than 4% of k_2) and could not be unambiguously established. The value of K_a obtained from the kinetic results is reasonable in view of the free ligand value.[12] The product of the reaction is the pyridine bonded complex of $(OH_2)_5Cr^{3+}$ and indicates an inner-sphere reduction.

Linkage Isomers of 4-Cyanopyridine. The rate data for reduction of the complexes are given in Table IV. The reduction of the nitrile-bonded isomer is inversely dependent on the hydrogen ion concentration and obeys the same rate law (eq 7) as found for the analogous 3-cyanopyridine complexes. Thus the data are consistent with a system having protonated and deprotonated Co(III) species in rapid equilibrium which are reduced at different specific rates. This leads to the derived rate law shown in eq 11. A plot of k_{obsd} (M^{-1} sec^{-1}) vs. $[H^+]^{-1}$ for this system is similar to Figure 1, except that the levelling-off area is not nearly so well defined. However, in this case $k_2K_a \gg k_1[H^+]$ for the entire range of acidities studied and plots of $1/k_{obsd}$ vs. $[H^+]$ gave good straight lines as expected. A nonlinear least-squares fit of the data to eq 7 gave k_2 = 6370, 6700, and 7010 M^{-1} sec^{-1} and K_a = 0.048, 0.051, and 0.053 M at 25.0, 34.4, and 43.4°C, respectively. The values for k_1 could not be established. For k_2, $\Delta H^{\ddagger}$ was 0.3 ± 0.3 kcal mol^{-1} and $\Delta S^{\ddagger}$ −40 ± 4. The product of the reaction, formulated as **4**, indicates a remote attack inner-sphere reaction.

The reduction of the complex coordinated through the pyridine nitrogen follows the rate law

$$-\frac{d \ln [\text{Co(III) complex}]}{dt} = k[Cr^{2+}] = k_{obsd} \quad (12)$$

Since the product of the reduction was identical with that obtained by reduction of the nitrile-bonded isomer and presumably **4**, the rate of reduction was followed at different wavelengths in hopes of detecting an intermediate. At 290 nm the stopped-flow traces showed an increase in absorbance followed by a decrease. When these data were analyzed in terms of two consecutive reactions, it was found that the rise in absorbance corresponded to the reduction of the complex (as determined at 470 nm). Furthermore, the second reaction was found to depend on the chromium(II) concentration and also had a dependence on the hydrogen ion concentration analogous to that found for the reduction of the nitrile-coordinated $(NH_3)_5Co^{3+}$ complexes. A reaction scheme consistent with these results, and also consistent with the fact that virtually 100% of the ligand was transferred, is given in eq 13.

$$(NH_3)_5CoN\langle\bigcirc\rangle-CN^{3+} + Cr^{2+} \longrightarrow \left[(OH_2)_5CrN\equiv C-\langle\bigcirc\rangle-N^{3+}\right] \overset{H^+}{\rightleftharpoons} \underset{\mathbf{5}}{\left[(OH_2)_5CrN\equiv C-\langle\bigcirc\rangle-NH^{4+}\right]} + Co^{2+} \xrightarrow{Cr^{2+}} (OH_2)_5CrN\langle\bigcirc\rangle-CN^{3+} + Cr^{2+} \quad (13)$$

4, final stable product

A summary of the rate constants obtained at 290 nm for the reduction of the cobalt(III) pyridine-bonded complex and the chromium(III) nitrile-bonded complex is given in Table V. The data for reduction of the Co^{3+} complex are in good agreement with that obtained at 470 nm where only cobalt(III) reduction is observed. The rate constants for reduction were 124, 129, and 135 M^{-1} sec^{-1} at 25.1, 34.6, and 43.3°C, respectively. These values gave $\Delta H^{\ddagger} = 0.2 \pm 0.3$ kcal mol^{-1} and $\Delta S^{\ddagger} = -48 \pm 4$ eu. The values obtained for reduction of the chromium(III) nitrile-bonded complex are not as well established because of the difficulty of curve-fitting when the disappearance of intermediate is faster than the reduction which produces the intermediate. However, the rate constants are clearly inversely dependent on $[H^+]$ in a manner similar to reduction of the cobalt(III) nitrile-bonded isomer indicating a similar mechanism. Analysis of the rate constants with respect to $[H^+]$ gives a rate constant for reduction of **5** equal to 7100 ± 500 M^{-1} sec^{-1} at 25°.

The reduction of **4** with chromium(II) was also attempted but no reaction was observed.

Discussion

The reduction of the linkage isomers of 4-cyanopyridine, I and II, has been shown to proceed by remote attack of the

Table V. Data Obtained for Reduction of II and 5 by Chromium(II)[a]

$10^3 \times$ [Co(III)], M	$10^3 \times$ [Cr(II)], M	[H^+], M	k_1 (Co redn),[b] sec^{-1}	k (Co redn), M^{-1} sec^{-1}	k_2 (Cr redn),[b] sec^{-1}	k_{obsd} (Cr redn), M^{-1} sec^{-1}
1.1	11.0	0.223	1.38	125	44.3	4000
1.1	11.0	0.223	1.34	122	42.5	3860
1.1	11.0	0.493	1.33	121	30.0	2730
1.1	11.0	0.493	1.32	120	30.1	2740
0.94	11.0	1.00	1.26	115	16.6	1510
0.96	8.00	1.00	0.932	117	13.0	1630
1.2	22.0	1.00	2.71	123	23.0	1500
1.2	22.0	1.00	2.45	112	30.7	1400
1.2	22.0	1.00	2.38	108	32.5	1500

[a] Ionic strength is 1.0 M with $LiClO_4$; λ. 290 nm. [b] Obtained from computer analysis of a consecutive reaction scheme shown in eq 1.

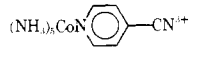
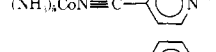
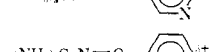
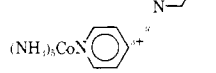
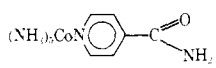
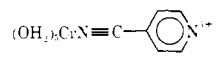
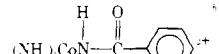
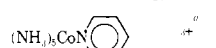
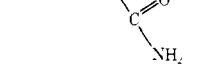
reductant at the pyridine and nitrile nitrogens, respectively. The reduction of I leads directly to the product **4**. Since the reduction of II also leads to the same product, an intermediate nitrile-bonded chromium(III) complex is likely formed. It is this intermediate which is reduced to give the final stable product. To a first approximation, one could consider the "reducibilities" of I and II to be the same since the $(NH_3)_5Co^{3+}$ group probably does not perturb the π orbitals on the ligand to any great extent. Therefore, the factor of 50 difference in the reduction rates could be attributed to the ability of the pyridine nitrogen vs. the nitrile nitrogen to bind to the reducing agent. One would expect the relatively "hard" pyridine nitrogen to be a more effective Lewis base toward the "hard" acid chromium(II) than the "soft" nitrile nitrogen.

In an attempt to obtain a more detailed picture of the reducibility of the ligand, an INDO/1[13] calculation was carried out on 4-cyanopyridine. The purpose was to determine the energy and symmetries of the frontier molecular orbitals. The calculation produced a lowest empty molecular orbital (*LEMO*) of −0.67 eV, suggesting that the ligand would accept an electron even in the gas phase. In solution, the tendency to accept an electron would be even more favorable due to solvent interactions. In the parent molecule, pyridine, the LEMO is calculated to have orbital energy 0.27 eV; in general, substitution of a cyano group has lowered the entire manifold of the π orbitals of the pyridine moiety. The $b_1\pi$ antibonding orbital of 4-cyanopyridine (the LEMO) is concentrated on the pyridine ring system (~83%), whereas 17% remains on the nitrile C–N system. Furthermore, 22% of this orbital resides on the pyridine nitrogen and only 10% on the nitrile nitrogen. Thus it may be easier for the reductant to add an electron to the $b_1\pi^*$ orbital by attack at the remote pyridine nitrogen in linkage isomer I than via attack at the remote nitrile nitrogen in linkage isomer II. The next lowest empty π molecular orbital is calculated of a_2 symmetry, and cannot accept and transmit the electron because of the node through the pyridine nitrogen and the C–N of the nitrile group. These results could be consistent with a radical-ion mechanism for reduction of both I and II, where electron transfer into the $b_1\pi^*$ system is rate determining. The rates can be rationalized in terms of the relative availability of the LEMO at both ends of the molecule. The calculation predicts that it will be easier to add an electron to the $b_1\pi^*$ system via the pyridine nitrogen, and thus isomer I should be more easily reduced by this mechanism.[14]

INDO/1 calculations on other 3- and 4-substituted pyridines[15] and benzonitriles indicate that both the energy of the LEMO as well as the stability of the precursor complex are important in determining the rate and mechanism of electron transfer. Quantitative correlations are not possible since the stability constants are not available.[16]

The data for reduction of the cyanopyridine complexes as well as other pyridine complexes are given in Table VI. As

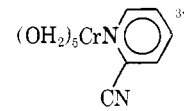
Table VI. Summary of Kinetic Parameters for Reduction of Pyridine Complexes of $(NH_3)_5Co^{3+}$ by Chromium(II)

Complex	k, M^{-1} sec^{-1} 25°	$\Delta H^{\ddagger}$, kcal mol^{-1}	$\Delta S^{\ddagger}$, eu
	124	0.2	−48
	6370	0.3	−40
	2.67	7.6	−31
	$\geq 1.6 \times 10^4$		
	4.0×10^{-3}	9	−39
	17.4	3.9	−40
	7100		
	1.31×10^5	1.3	−31
	3.3×10^{-2} (i.s.) 1.4×10^{-2} (o.s.)	10 9	−31 −36

[a] Reference 5; i.s. = inner sphere; o.s. = outer sphere. [b] Reference 8.

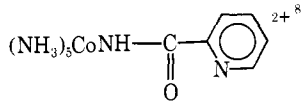
mentioned previously, an intermediate of formulation **5** was observed, and the final product in this reaction was **4**. This allowed us to obtain a rate constant for reduction of the intermediate, and this is also given in Table VI. Using the arguments of Nordmeyer and Taube,[5] we would conclude that the linkage isomer I reacts via a radical-ion mechanism. On the other hand, reduction of II, cannot be assigned to a radical-ion mechanism owing to the fact that no reduction was observed in the reaction of **4** with chromium(II).

The reduction of 2-cyanopyridine complex appears to proceed via attack at the uncoordinated pyridine nitrogen resulting in the initial formation of



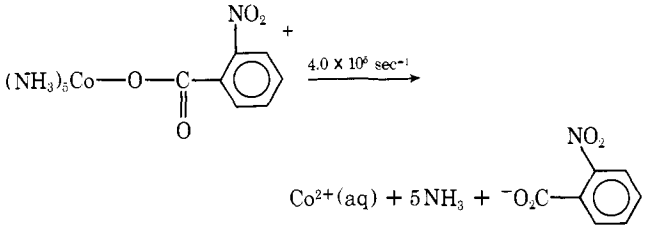
This complex rearranges to form the chelate III. The mechanism shown in eq 6 indicates that intramolecular nucleophilic attack of a coordinated water molecule can result in formation of the chelate. Intramolecular nucleophilic attack of a coordinated hydroxide on a nitrile carbon has been observed in a related complex.[17] Identification of the final product as the chelate is based on the fact that the product

from the reduction of the 2-cyanopyridine complex is identical with the product from the chromium(II) reduction of **6**.[8] It may well be that for the 2-substituted pyridines, the



6

ligand functions solely as a binding group to bring the reductant close enough to the oxidant for resonance transfer to occur rather than radical formation. Cohen and Meyerstein[18] have suggested that the intramolecular electron transfer which occurs in the reaction[19]



may take place by mediation of the electron through one of the adjacent ammine ligands. In the case of 2-cyanopyridine, mixing between the orbitals on the reductant and oxidant may take place as a result of binding to the pyridine nitrogen and direct transfer may be possible or, if a radical is formed, adjacent mediation could also occur.

The reduction of the 3-cyanopyridine complex also proceeds by remote attack with formation of **3**. In this case, only about 55% of the product above was isolated. However, based on the outer-sphere rates of reduction of the pyridine and nicotinamide complexes of 0.004 and 0.014 M^{-1} sec^{-1}, respectively,[5] reduction of the 3-cyanopyridine complex probably occurs predominantly by an inner-sphere process.

Acknowledgment. The author wishes to thank the National Research Council of Canada for financial support of this research.

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(14) The analysis assumes the integrity of the ligand orbitals is retained in the complexes. For cobalt(III), this assumption seems reasonable.
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(16) However, see D. V. Sokol'skii, Ya. A. Dorfman, and Kh. D. Koshymbekov, *Dokl. Akad. Nauk SSSR*, **217**, 143 (1974).
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Synthesis of 3-Deazaguanine, 3-Deazaguanosine, and 3-Deazaguanylic Acid by a Novel Ring Closure of Imidazole Precursors

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Abstract: 3-Deazaguanine [6-aminoimidazo[4,5-*c*]pyridin-4(5H)-one (**4**)], 3-deazaguanosine [6-amino-1-β-D-ribofuranosylimidazo[4,5-*c*]pyridin-4(5*H*)-one (**17**)], and 3-deazaguanylic acid [6-amino-1-β-D-ribofuranosylimidazo[4,5-*c*]pyridin-4(5*H*)-one 5′-phosphate (**24**)] have been synthesized for the first time by a novel base-catalyzed ring closure of 5(4)-cyanomethylimidazole-4(5)-carboxamide (**3**), 5-cyanomethyl-1-β-D-ribofuranosylimidazole-4-carboxamide (**12**), and 5-cyanomethyl-1-β-D-ribofuranosylimidazole-4-carboxamide 5′-phosphate (**23**), respectively. The imidazole **3** was prepared from the ammonolysis of methyl 5(4)-cyanomethylimidazole-4(5)-carboxylate (**2**). The imidazole nucleoside **12** was obtained from the stannic chloride-catalyzed condensation of methyl 5(4)-cyanomethyl-1-trimethylsilylimidazole-4(5)-carboxylate (**5**) and a fully acylated β-D-ribofuranose (**6** or **7**), followed by ammonolysis of the blocking groups and the ester function. The imidazole nucleotide **23** was obtained from the phosphorylation of **12** with phosphoryl chloride in trimethyl phosphate. The yield and ratio of the ribofuranosyl derivatives of imidazole **2** markedly depends on the ratio of stannic chloride to trimethylsilylimidazole **5** and the fully acylated β-D-ribofuranose. The structures of the nucleosides were established by the use of carbon-13 and proton NMR. 3-Deazaguanine (**4**), 3-deazaguanosine (**17**), and 3-deazaguanylic acid (**24**) have demonstrated a potent broad spectrum activity in vitro against various DNA and RNA viruses, as well as potent in vivo activity against L1210 leukemia and adenocarcinoma 755 in mice.

3-Deazaguanine [6-aminoimidazo[4,5-*c*]pyridin-4(5*H*)-one (**4**)] is the only 3-deaza analogue of the ubiquitous naturally occurring purines whose synthesis has not been realized. 3-Deaza analogues of uric acid,[2] xanthine,[2] hypoxanthine,[3] adenine,[3] and the chemotherapeutically useful 6-thioguanine[4a] and 6-mercaptopurine[4a] have been reported. Furthermore, the nucleoside and nucleotide derivatives of 3-deazaadenine and 3-deazahypoxanthine have been prepared.[5] Poly-3-deazaadenylic acid and poly-1-deazaadenylic acid have been enzymatically prepared from their corre-