0.25 g (43%) (mp 208 °C) of dark brown crystals of $PPh_3Co(DH)_2Cl$ or 0.25 g (57%) (mp 248 °C) of light brown crystals of $pyCo(DH)_2Cl$.

Anal. Calcd for $PPh_3Co(DH)_2Cl$ ($C_{26}H_{29}ClCoN_4O_4P$): C, 53.19; H, 4.98; N, 9.95. Found: C, 53.27; H, 5.45; N, 9.24. Molecular weight for $PPh_3Co(DH)_2Cl$: calcd, 587.0; found ($CHCl_3$), 625.0.

Anal. Calcd for $pyCo(DH)_2Cl$ ($C_{13}H_{19}ClCoN_5O_4$): C, 38.68; H, 4.74; N, 17.35. Found: C, 38.64; H, 4.57; N, 16.93.

If these same complexes are left in contact with concentrated aqueous HCl for a long time, $CoCl_2 \cdot 6H_2O$ precipitates.

Treatment of 0.53 g (1 mmol) of $PPh_3Co(DH)_2N_3$ or 0.41 g (1 mmol) of $pyCo(DH)_2N_3$ in 50 mL of acetone with 5 mL of 70% $HClO_4$ produces upon addition of ether $[PPh_3Co(DH)_2]^+ClO_4^-$ or $[pyCo(DH)_2]^+ClO_4^-$. Addition of $NaBPh_4$ in ethanol to the $[PPh_3Co(DH)_2]^+ClO_4$ solution precipitates $[PPh_3Co(DH)_2]^+BPh_4^-$ as follows. Anal. Calcd for $C_{26}H_{29}ClCoN_4O_8P$ (0.51 g, 79%; $[PPh_3Co(DH)_2]^+ClO_4^-$: C, 47.97; H, 4.50; N, 8.61. Found: C, 46.88; H, 4.78; N, 7.97. Anal. Calcd for $C_{13}H_{19}ClCoN_5O_8$ (0.33 g, 72%; $[pyCo(DH_2)]^+ClO_4^-$): C, 34.41; H, 4.23; N, 12.35. Found: C, 34.07; H, 5.01; N, 11.94. Anal. Calcd for $C_{50}H_{49}BCoN_4O_4$ (0.54 g, 88%; $[PPh_3Co(DH)_2]^+BPh_4^-$): C, 71.51; H, 5.89; N, 6.67. Found: C, 69.24; H, 5.04; N, 7.19.

Acknowledgment. Support of this research by Deutsche Forschungsgemeinschaft, Fonds der Chemischen Industrie, and the Research Advisory Board of the University of Nevada, Reno, is gratefully acknowledged.

Registry No. **1a**, 80462-11-9; **1b**, 80462-10-8; **1c**, 80462-09-5; **1d**, 80462-08-4; **1e**, 80462-07-3; **1f**, 80462-06-2; **1g**, 80462-05-1; **1h**, 80462-04-0; **1i**, 80462-03-9; **1j**, 80462-02-8; **1k**, 80462-01-7; **1l**, 80462-00-6; **1m**, 80461-98-9; **1n**, 80461-97-8; **1o**, 80462-40-4; **1p**, 80462-38-0; **1q**, 80462-37-9; **2a**, 80462-36-8; **2b**, 80462-35-7; **2c**, 80462-34-6; **2d**, 80462-33-5; **2e**, 80462-31-3; **2f**, 80462-30-2; **3a**, 80462-39-1; **4a**, 80462-29-9; **5a**, 80462-28-8; **6a**, 80462-27-7; **6b**, 80462-26-6; **6c**, 80462-25-5; **7a**, 80462-24-4; **7b**, 80462-23-3; **8a**, 80462-22-2; **9a**, 80462-21-1; **10a**, 80471-14-3; **10b**, 80462-20-0; **11a**, 80462-19-7; **12a**, 77172-84-0; **12b**, 30786-24-4; 1,4-dichlorobutyne-2, 821-10-3; propargyl alcohol, 107-19-7; propargyl bromide, 106-96-7; 4,5-bis(methoxycarbonyl)-1,2,3-triazole, 707-94-8; diethyl maleate, 141-05-9; $C_8H_9N_3O_5$, 80461-78-5; $(EtO_2C)_2(H_2C_2N_3)Co(DH)_2NH_3$, 80462-18-6; $CH_3SCNCO(DH)_2CN$, 80462-53-9; $PPh_3Co(DH)_2Cl$, 23295-34-3; $pyCo(DH)_2Cl$, 23295-32-1; $[PPh_3Co(DH)_2]^+ClO_4^-$, 80462-52-8; $[pyCo(DH)_2]^+ClO_4^-$, 80513-21-9; $[PPh_3Co(DH)_2]^+BPh_4^-$, 80462-51-7; $PPh_3Co(DH)_2N_3$, 69879-86-3; $MePPh_2Co(DH)_2N_3$, 80462-49-3; $Me_2PPhCo(DH)_2N_3$, 80462-48-2; $PBu_3Co(DH)_2N_3$, 51194-39-9; $P(Bzl)_3Co(DH)_2N_3$, 80462-47-1; $P(OCH_3)_3Co(DH)_2N_3$, 61024-83-7; $P(OPh)_3Co(DH)_2N_3$, 70106-13-7; $PhNH_2Co(DH)_2N_3$, 66496-40-0; $pyCo(DH)_2N_3$, 56589-86-7; $NH_3Co(DH)_2N_3$, 66496-39-7; 1-MeImCo$(DH)_2N_3$, 80462-46-0; $AsPh_4[Co(DH)_2(N_3)_2]$, 43128-64-9; $PBu_3Co(DPH)_2N_3$, 80462-45-9; $[Co[(DO)(DOH)pn](N_3)_2]$, 69879-56-7; $PPh_3Co(Salen)N_3$, 70106-20-6; $PPh_3Co(Salphen)N_3$, 62858-89-3; *cis*-$PPh_3Co(acac)_2N_3$, 70100-51-5; pyCo(Salphen)N_3, 69907-81-9; $CH_3CO_2C{\equiv}CCO_2CH_3$, 762-42-5; $HC{\equiv}CCO_2Et$, 623-47-2; $HC{\equiv}CC(O)H$, 624-67-9; $HC{\equiv}CCH(O_2CCH_3)_2$, 67088-67-9; $NCCF_3$, 353-85-5; $NCCO_2C_2H_5$, 623-49-4; $NCCH_2CN$, 109-77-3.

Contribution from the Department of Chemistry,
Kent State University, Kent, Ohio 44242

Electron Transfer. 51. Reactions of Riboflavin Radicals with Metal-Center Oxidants[1]

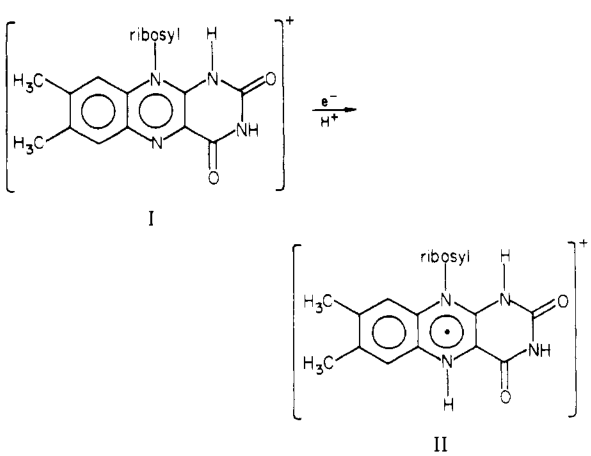
A. N. SINGH, E. GELERINTER, and E. S. GOULD*

Received June 19, 1981

Riboflavin undergoes successive one-electron reductions by Eu^{2+} or V^{2+} in aqueous $HClO_4$, giving first the radical ion, II, and then the dehydro compound, III. Specific rates (21 °C, 0.12 M $HClO_4$) for the two V^{2+} reductions are 8.0×10^4 and 3.6×10^4 M^{-1} s^{-1}, both far above the substitution-controlled upper limit for inner-sphere V(II) reactions. Calculated formal potentials for the two reductions in 1 M H^+ are 0.220 and 0.150 V. Rates of reactions of the radical cation Rb· with Hg^{2+}, $(NH_3)_5CoBr^{2+}$, and the *N,N*-dimethylnicotinamide derivative of $(NH_3)_5Co^{III}$ (IV) are inversely proportional to $[H^+]$ (in the range of 0.7–1.3 M H^+), indicating that the flavin radical cation is undergoing partial deprotonation to the active reducing species. Reactivity patterns for reductions of $(NH_3)_5Co^{III}$ complexes by the radical are devoid of those substituent effects that characterize inner-sphere reductions by transition-metal centers but resemble instead the pattern for reductions by the outer-sphere reagent $Ru(NH_3)_6^{2+}$. This similarity, in conjunction with the characterization of the oxidation product as riboflavin (with the ring system apparently unaltered), indicates that reductions by Rb· of these complexes follow outer-sphere paths. Specific rates of reaction of Rb· (25 °C, 1.3 M $HClO_4$) with the oxidizing metal centers Fe^{3+}, Tl^{3+}, Cu^{2+}, Hg^{2+}, VO^{2+}, and UO_2^{2+} are not related simply to oxidation potential, ionic charge, electronic structure, self-exchange rates, or the accessibility of an oxidation state lying one unit below.

Among the oxidation coenzymes, flavin derivatives rank second to none in importance and diversity of role.[2] Much of their versatility reflects the ease with which the isoalloxazine unit, a general feature of the class, can participate in both one- and two-electron transactions, leading to the ability to mediate between electron-transfer processes and the even-electron processes characterizing metabolic conversions.

The impetus for the present work, which deals principally with the reactions of protonated riboflavin (I) and its reduced radical cation or semiquinone derivative (II) with metal-centered electron-transfer species, was the expectation that flavins, because of their dual redox functionality, might catalyze re-



I

II

(1)

---

(1) Joint sponsorship of this work by the donors of the Petroleum Research Fund, administered by the American Chemical Society, by the National Science Foundation (Grant 8022881), and by the Biomedical Research Support Grant Program, Division of Research Resources, National Institutes of Health (Grant BRSG S07 RR-07182), is gratefully acknowledged.

(2) See, for example: (a) Walsh, C. *Annu. Rev. Biochem.* **1978**, *47*, 881. (b) Metzler, D. E. "Biochemistry"; Academic Press: New York, 1977; p 476. (c) Hemmerich, P. *Adv. Chem. Ser.* **1977**, *No. 162*, 312. (d) Mayhew, S. G.; Ludwig, M. L. *Enzymes, 3rd Ed.* **1975**, *12*, 47. (e) Hemmerich, P.; Veeger, C.; Wood, H. C. S. *Angew. Chem., Int. Ed. Engl.* **1965**, *4*, 671.

actions between noncomplementary inorganic reagents (an oxidant and reductant that change by different electron numbers). Although we have found no clear example of such catalysis, we here report observations that add detail to the present picture of the redox behavior of this class of coenzymes.[3,4]

Table I. Electronic Spectra of Riboflavin at Three Oxidation Levels in 1.0 M $HClO_4$

	λ_{max}, nm (ϵ^a)
riboflavin, protonated form (I)	388 (18.0), 264 (35.0), 218 (27.0)
radical cation (II)^b	495 (9.0), 374 sh (8.1), 354 sh (12.7), 334 sh (11.5), 318 sh (9.3), 256 (39.3), 210 (32.3)
dihydro product (III)^c	312 (11.9), 292 sh (9.0), 246 sh (13.6), 226 sh (24.2), 208 (39)

^{a} ϵ values in M^{-1} cm^{-1} × 10^{-3}. ^{b} Prepared by treatment of I with 1.01 equiv of $V(ClO_4)_2$. Values of ϵ calculated by taking into account the partial disproportionation of II in this medium.[11] ^{c} Prepared by treatment of I with 10.0 equiv of $V(ClO_4)_2$.

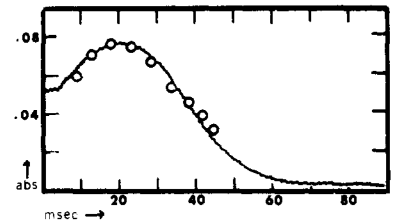


Figure 1. Kinetic profile of the reduction of riboflavin (1.0×10^{-5} M) with $V(ClO_4)_2$ (1.24×10^{-3} M) in 0.12 M $HClO_4$, showing the formation and destruction of the radical cation II. Reaction was carried out at 21 °C and $\mu = 0.12$; $\lambda = 495$ nm; mixing time = 4.5 ms; optical path length = 2.0 cm. Circles denote values calculated from eq 3 (see text), with $t_{max} = 16$ ms, $k_1 = 100$ s^{-1}, and $k_2 = 45$ s^{-1}.

Experimental Section

Materials. Riboflavin, an Aldrich product, was used as received; master solutions, 0.001 M in coenzyme, were prepared in deaerated 1.0 M $HClO_4$ before each series of experiments. Solutions of the perchlorates of Eu(II),[5] V(II),[6] and V(III)[7] were prepared as described. Master solutions of $UO_2(ClO_4)_2$, $Fe(ClO_4)_3$, and $Cu(ClO_4)_2$ were prepared from the hydrated perchlorates (Alfa products) and were standardized spectrophotometrically as described.[8] Cobalt complexes not available from previous studies[9] were prepared by literature procedures.[9a,10,11]

Formation of the Riboflavin Radical Cation (II) and the Dihydro Derivative (III). Reduction products of riboflavin (Rb) were prepared in solution by treatment of solutions of riboflavin (Rb) in 1.0 M $HClO_4$ with measured quantities of Eu(II) or V(II). All preparations and reactions were carried out under nitrogen. Addition of less than 1 equiv of reductant produced the characteristic red color ($\lambda_{max} = 495$ nm) of the radical cation II; more than 1 equiv caused progressive fading until, at slightly more than 2.0 equiv, the red color was imperceptible, indicating virtually complete conversion to the dihydro form. Solutions of the latter, in the absence of excess reductant, quickly darken, due principally to reaction with traces of O_2. Spectral characteristics of the three oxidation levels in 1 M $HClO_4$ are summarized in Table I. Reductions with 10^{-3} M Eu^{2+} were too rapid to follow, even under stopped-flow conditions, but kinetic profiles of the reduction with 10^{-3} M V^{2+} in 0.12 M $HClO_4$ (Figure 1) indicated two successive steps having comparable specific rates.

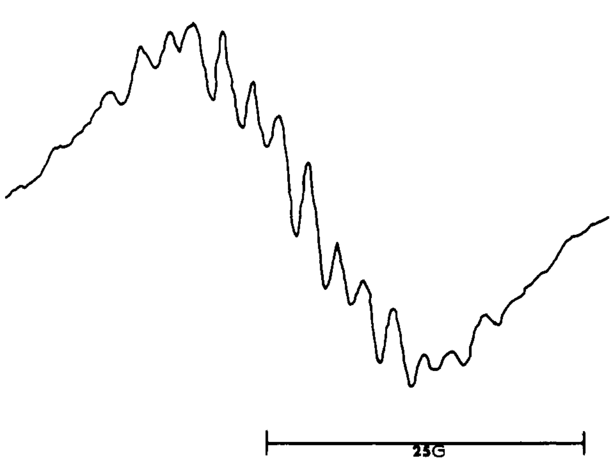


Figure 2. ESR spectrum of the riboflavin radical cation II (Varian V-4500 X-band spectrometer) in 88% aqueous ethanol. The generating solution was 3×10^{-4} M in riboflavin, 4×10^{-4} M in Eu^{2+}, and 0.4 M in $HClO_4$. The spectrum was taken 3 min after mixing. The center of spectrum is at $g = 1.99$.

For ESR measurements, with a Varian V-4500 X-band spectrometer, solutions were made in 88% aqueous ethanol and were 3×10^{-4} M in riboflavin, 4×10^{-4} M in Eu^{2+}, and 0.4 M in $HClO_4$. The spectrum (Figure 2), featuring 14 distinct peaks and vestiges of 4 more, was more satisfactorily resolved than that reported earlier for this radical cation in aqueous HCl,[11] being, at the same time, closely similar to that observed for lumiflavin semiquinone in strong acid.[12] It disappeared when the red radical cation was exposed to air or was treated with more than a 2-fold excess of Eu(II) or V(II).

Rate Measurements. Rates of reaction of the radical with metal-center oxidants were estimated from measurements of absorbance changes (at 495 nm) on a Cary 14 spectrophotometer.[9c] The radical was first generated by treatment of riboflavin in $HClO_4$–$LiClO_4$ with a measured quantity of $Eu(ClO_4)_2$ or $V(ClO_4)_2$. So that complications from reaction of the added oxidant with the dihydro derivative, III (formed from disproportionation of the radical) could be minimized, riboflavin was kept in large excess (6- to 8-fold) over the reductant. It was further necessary to carry out the reactions of interest in a 10-cm (volume 30 cm^3) rather than a 1-cm optical cell. When these conditions were not used, kinetic curves exhibited a prominent pseudo-second-order contribution (presumably reflecting the preequilibrium $2Rb\cdot \rightleftarrows Rb{:} + Rb$) superimposed on the primary pseudo-first-order reaction. Oxidations in which $[H^+] < 0.7$ M invariably yielded badly distorted kinetic curves despite a variety of attempted modifications in our procedures. Reactions were first order both in radical and oxidant but were generally run with the ratio $[oxidant]/[Rb\cdot]$ greater than 8. When the effect of $[H^+]$ variation was being examined, the concentration of added $HClO_4$ was allowed to vary between 0.7 and 1.3 M while total ionic strength was kept near 1.3 M by addition of thrice-recrystallized $LiClO_4$. Curves representing at least 4 half-lives were obtained for the more rapid reactions, but specific rates for the slower reactions were estimated from initial rates, with correction applied for the slow consumption of radical (possibly by gradual leakage of atmospheric oxygen) in the absence of added oxidant. For the faster reactions, rate constants obtained from successive half-life values within a run agreed to within 6%, whereas specific rates from replicate runs checked to better than 8%. Specific rates obtained from initial slopes agreed to within 10%. Temperatures were kept at 25.0 ± 0.2 °C during the entire series of kinetic runs.

---

(3) Interactions of flavin species with metal ions, both in aqueous[4a,b] and in nonaqueous[4c] media, have been studied, but emphasis has been on ligation processes rather than electron transfer.

(4) See, for example: (a) Baanda, I. F.; Metzler, D. E. *Biochim. Biophys. Acta* **1961**, *50*, 403. (b) Bamberg, P.; Hemmerich, P. *Helv. Chim. Acta* **1962**, *44*, 1001. (c) Sawyer, D. T.; McCreery, R. L. *Inorg. Chem.* **1972**, *11*, 779.

(5) Dockal, E. R.; Gould, E. S. *J. Am. Chem. Soc.* **1972**, *94*, 6673.

(6) (a) Guenther, P. R.; Linck, R. G. *J. Am. Chem. Soc.* **1969**, *91*, 3769. (b) Linck, R. G. *Inorg. Chem.* **1970**, *9*, 2529.

(7) Srinivasan, V. S.; Hu, Y.-R.; Gould, E. S. *Inorg. Chem.* **1980**, *19*, 3470.

(8) "IUPAC Spectrophotometric Data"; Butterworths: London, 1963; pp 149 (Cu^{II}), 223 ($Fe^{I}I^{I}$), 550 (UO_2^{2+}).

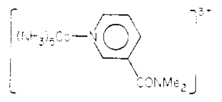
(9) (a) Fan, F.-R. F.; Gould, E. S. *Inorg. Chem.* **1974**, *13*, 2639. (b) Fanchiang, Y.-T.; Carlson, R. R.; Thamburaj, P. K.; Gould, E. S. *J. Am. Chem. Soc.* **1977**, *99*, 1073. (c) Wu, M.-Y.; Paton, S. J.; Fanchiang, Y.-T.; Gelerinter, E.; Gould, E. S. *Inorg. Chem.* **1978**, *17*, 326.

(10) Gould, E. S.; Taube, H. *J. Am. Chem. Soc.* **1964**, *86*, 1318.

(11) Ogura, Y.; Nakamura, S.; Nakamura, T. *Acta Chem. Scand.* **1963**, *17*, S184.

(12) Guzzo, A. V.; Tollin, G. *Arch. Biochem. Biophys.* **1964**, *105*, 380.

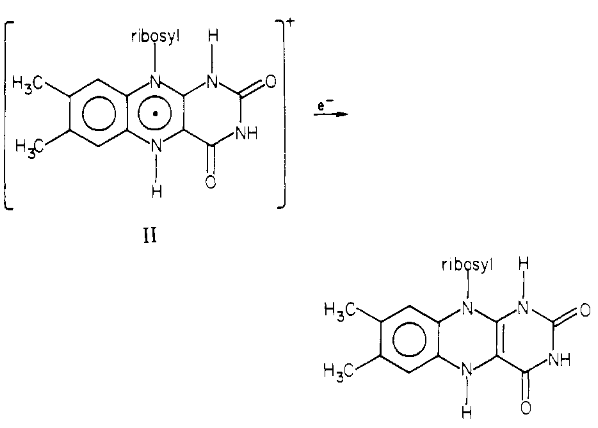
Table II. Kinetic Data for Reactions of the Riboflavin Cation Radical with Metal-Center Oxidants[a]

oxidant	$[H^+]$, M	k, M^{-1} s^{-1}
$(NH_3)_5CoBr^{2+}$	0.70	9.2
	0.90	7.6
	1.10	6.5
	1.30	5.3
 IV	0.70	2.0
	0.90	1.62
	1.10	1.21
	1.30	0.99
Hg^{2+}	0.70	30
	0.90	22
	1.10	17.1
	1.30	15.2

[a] Reactions were carried out at 25 °C with $\mu = 1.30$. $[Rb\cdot]_0 = 1.0 \times 10^{-5}$ M; [oxidant] = 0.0002–0.0012 M; [riboflavin] = 8×10^{-5} M. Rates were measured at 495 nm, by using a 10.0-cm cell (see Experimental Section).

Results and Discussion

Formation of the radical cation and its conversion to the dihydro compound, III, with use of excess V^{2+}, were monitored


II

III

(2)

at 495 nm. The kinetic curve (Figure 1) conforms to eq 3

$$\frac{A_t}{A_{max}} = \frac{e^{-k_1 t} - e^{-k_2 t}}{e^{-k_1 t_{max}} - e^{-k_2 t_{max}}} \qquad (3)$$

(which results from a superposition of two consecutive pseudo-first-order reactions) with the specific rate for formation (k_1) = 100 s^{-1}, that for destruction (k_2) = 45 s^{-1}, and the time for maximum absorbance (t_{max}) = 16 ms.[13] These parameters lead to second-order rate constants (21 °C, $\mu = 0.12$) 8.0×10^4 and 3.6×10^4 M^{-1} s^{-1} for the V^{2+} reductions of riboflavin and of its radical cation, II. Since these values lie far above 20–40 M^{-1} s^{-1}, the substitution-controlled upper limit for inner-sphere V(II) reductions,[14] both reductions must be taken to proceed nearly completely via outer-sphere paths. Note that k_1/k_2 in this system approaches 2, a ratio slightly less than that (ca. 10) applying to analogous stepwise Eu(II) reductions of pyridinecarboxylato species,[15] which are thought, however, to be inner-sphere processes.[16]

Table III. Specific Rates for Oxidations of the Riboflavin Cation Radical with Pentaamminecobalt(III) Complexes, $R(NH_3)_5Co^{III}$ [a]

ligand, R	k, M^{-1} s^{-1}
iodo	45
bromo	5.3
chloro	0.20
fluoro	0.11
aquo	0.50
N,N-dimethylnicotinamide (IV)	0.99
pyridine	0.29
N,N-dimethylformamide (O bound)	0.22
formato	0.15
benzoylformato	0.14

[a] Reactions were carried out at 25 °C in 1.3 M $HClO_4$. Details are given in Table II and in the Experimental Section.

Although direct measurement of the formal potential for the one-electron reduction of riboflavin is complicated by the relative ease with which the cation radical undergoes further reduction,[17] combination of the potential for the two-electron process (0.188 V[18]) with the comproportionation constant (I + III $\rightleftarrows$ 2II; $K = 15$ (1 M HCl)[11]) leads to the values of 0.220 and 0.150 V for successive one-electron reductions of the flavin. These are sufficiently positive to allow us to assume complete consumption of V^{2+} or Eu^{2+} when these reductants are added in deficiency.

Oxidations of the riboflavin radical cation with substitution-inert cobalt(III) complexes proceed at rates comparable to those of the quinoxalinium radical,[19] but complications due to competing reactions of the radical are somewhat less troublesome for the flavin species. Acidity dependencies are summarized in Table II for oxidations by two $(NH_3)_5Co^{III}$ derivatives and by Hg^{2+}. Within the relatively narrow range 0.7–1.3 M H^+ (imposed by experimental constraints associated with these systems) rates are seen to be inversely proportional to $[H^+]$, pointing to an activated complex containing one unit each of oxidant and radical, from which combination one proton has been removed. Because the cobalt complexes taken do not feature protons that are removed near the acidity range studied, it may be inferred that it is the flavin radical that is undergoing partial deprotonation to the active reducing species. Since there is no indication of kinetic saturation within the $[H^+]$ range examined, K_{HA} for this radical may be considered to fall well below 0.7 M.[20]

Specific rates for oxidation by a variety of $(NH_3)_5Co^{III}$ derivatives in 1.3 M $HClO_4$ are presented in Table III. The reactivity pattern for these oxidants is seen to be devoid of those substituent effects that characterize inner-sphere reductions by Cr(II),[21] Eu(II),[9a] and U(III).[22] There is no hint that

---

(13) See, for example: Espenson, J. H. "Chemical Kinetics and Reaction Mechanisms"; McGraw-Hill: New York, 1981; pp 65–70. As this author points out, the observed kinetic profile is equally consistent with a pair of reactions in which the rate constants are reversed, i.e., k_1 = 45 s^{-1} and k_2 = 100 s^{-1}. Calculation of the maximum degree of conversion to Rb· associated with the two sequences, thence the apparent exctinction coefficient of Rb·, yields values of 8×10^3 and 1.6×10^4 M^{-1} cm^{-1} for ϵ_{495}. Only the former value is consistent with that observed in static experiments (Table I).

(14) See, for example: (a) Hicks, K. W.; Toppen, D. L.; Linck, R. G. *Inorg. Chem.* **1972**, *11*, 310. (b) Sutin, N. *Acc. Chem. Res.* **1968**, *1*, 225.

(15) Singh, A. N.; Radlowski, C. A.; Reed, J. W.; Krishnamurthy, V. V.; Gould, E. S. *Inorg. Chem.* **1981**, *20*, 211. These authors suggest that addition of an electron to the pyridine ring entails a lower reorganizational barrier than addition of a second electron to the resulting pyridinyl radical since the radical, like the parent pyridine, is essentially aromatic (with all bonds in the ring nearly the same length), whereas the two-electron (dihydro) product features distinct single and double bonds. The barrier associated with addition of a second electron to the three-ring flavin system should be less marked since the dihydro product (III) retains considerable aromaticity.

(16) Fanchiang, Y.-T.; Thomas, J. C.; Neff, V. D.; Heh, J. C.-K.; Gould, E. S. *Inorg. Chem.* **1977**, *16*, 1942.

(17) See, for example: Dryhurst, G. "Electrochemistry of Biological Molecules"; Academic Press: New York, 1977; p 370.

(18) Brdička, R.; Knobloch, E. *Z. Elektrochem. Angew. Phys. Chem.* **1941**, *47*, 721.

(19) Chang, C.-R.; Paton, S. J.; Gelerinter, E.; Gould, E. S. *Inorg. Chem.* **1979**, *18*, 1294.

(20) Reported pK_{HA} values for substituted flavin radicals fall in the range 1–3.[2c]

(21) Taube, H.; Gould, E. S. *Acc. Chem. Res.* **1969**, *2*, 321.

(22) (a) Wang, R. T.; Espenson, J. H. *J Am. Chem. Soc.* **1971**, *93*, 380. (b) Loar, M. K.; Sens, M. A.; Loar, G. W.; Gould, E. S. *Inorg. Chem.* **1978**, *17*, 330.

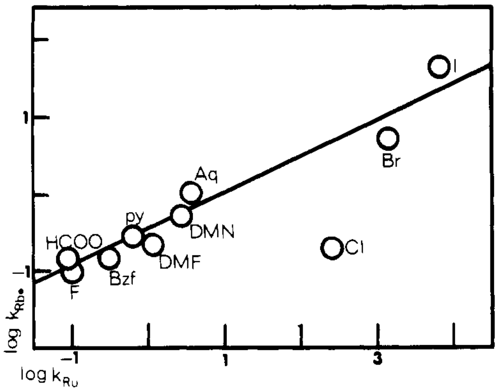


Figure 3. log–log plot comparing the specific rates of reduction of pentaamminecobalt(III) complexes, $R(NH_3)_5Co^{III}$, by $Ru(NH_3)_6^{2+}$ ($\mu = 0.50$; supporting electrolyte LiCl) and by the riboflavin radical cation (Rb·). The latter set was measured at 25 °C in 1.3 M $HClO_4$. Bzf = benzoylformato; DMN = *N,N*-dimethylnicotinamide (IV). The regression line shown, drawn with the point for $Co(NH_3)_5Cl^{2+}$ excluded from the calculation, corresponds to the equation log $k_{Rb\cdot}$ = 0.47 log k_{Ru} − 0.44, with a correlation coefficient of 0.979.

carboxyl bridging is significant, for the carboxylato complexes are reduced at rates close to those for the dimethylnicotinamide (IV) and pyridine derivatives, the structures of which dictate electron transfer predominantly or exclusively by an outer-sphere path.[23] Moreover, values for the benzoylformato and formato complexes are nearly the same, whereas in the Cr(II) and Eu(II) series the ratio of specific rates[9a] for this pair exceeds 10^3. Indeed, the pattern of rates for reduction by Rb·, which, even when the halopentaammine oxidants are included, embraces a modest range of 3×10^2, corresponds reasonably closely to the corresponding pattern for the outer-sphere reductant $Ru(NH_3)_6^{2+}$, the formal potential of which ($E°$ = 0.214 V)[24] lies close to the calculated value for the one-electron reduction of riboflavin in our medium. The absence of specific substituent effects, in conjunction with the characterization of the oxidation product as riboflavin (with the ring system apparently unaltered), indicates strongly that oxidations of Rb· by these Co(III) derivatives proceed by an outer-sphere path, as has been suggested[19] for oxidations of the closely related quinoxalinium radical.[25]

Table IV. Specific Rates for Oxidations of the Riboflavin Cation Radical Using Substitution-Labile Metal Centers[a]

oxidant	k, M^{-1} s^{-1}
Fe^{3+}	9×10^3
Tl^{3+}	5×10^3
Cu^{2+}	4×10^2
Hg^{2+}	15.2
VO^{2+}	0.06
UO_2^{2+}	0.02

[a] Reactions were carried out at 25 °C in 1.3 M $HClO_4$ with use of the metal perchlorates. Details are given in the Experimental Section.

The log–log plot comparing specific rates for reduction by Rb· in 1.3 M $HClO_4$ to those[26] for reduction by $Ru(NH_3)_6^{2+}$ (Figure 3) is seen to approach linearity, with the point for $Co(NH_3)_5Cl^{2+}$ unaccountably divergent. We find that the two series of reductions conform to the relationship

$$\log k_{Rb\cdot} = 0.47 \log k_{Ru} - 0.44 \qquad (4)$$

The greater sensitivity of the $Ru(NH_3)_6^{2+}$ rates to structural alteration brings to mind related comparisons made by Hua[27] and, earlier, by Linck,[6a] but has not yet been satisfactorily explained.

In an initial attempt to extend this study to substitution-labile metal centers, we have encountered four oxidants (Cu^{2+}, Hg^{2+}, VO^{2+}, and UO_2^{2+}) that react with Rb· at rates that can be monitored by conventional mixing techniques and two oxidants (Fe^{3+} and Tl^{3+}) whose reactions fall into the stopped-flow region. Acidity dependence has been determined for only one of these (Hg^{2+}, Table II), and this is seen to follow an inverse [H^+] rate law, as do the substitution-inert Co(III) oxidants. Specific rates at 25 °C in 1.3 M $HClO_4$ (Table IV) do not appear to be related in any straightforward fashion to oxidation potential, ionic charge, electronic structure, self-exchange rates (insofar as they are known), or the accessibility of a stable oxidation state one unit below. More detailed studies are needed here before additional comments are justified.

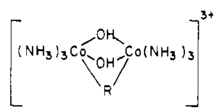
Registry No. I, 66610-20-6; II, 78692-23-6; III, 13345-95-4; riboflavin, 83-88-5; V, 7440-62-2; $(NH_3)_5CoBr^{2+}$, 14970-15-1; IV, 31011-70-8; Hg, 7439-97-6; $(NH_3)_5CoI^{2+}$, 15392-08-2; $(NH_3)_5CoCl^{2+}$, 14970-14-0; $(NH_3)_5CoF^{2+}$, 15392-06-0; $(NH_3)_5Co(H_2O)^{3+}$, 14403-82-8; $(NH_3)_5Co(py)^{3+}$, 31011-67-3; $(NH_3)_5Co(DMF)^{3+}$, 31125-61-8; $(NH_3)_5Co(HCOO)^{2+}$, 19173-64-9; $(NH_3)_5Co(PhCOCOO)^{2+}$, 49861-82-7; Fe, 7439-89-6; Tl, 7440-28-0; Cu, 7440-50-8; VO^{2+}, 20644-97-7; UO_2^{2+}, 16637-16-4; Eu, 7440-53-1.

---

(23) Gould, E. S. *J. Am. Chem. Soc.* **1967**, *89*, 5792.

(24) Endicott, J. F.; Taube, H. *Inorg. Chem.* **1965**, *4*, 437.

(25) In contrast, preliminary experiments dealing with the oxidation of the riboflavin cation radical with bridged dimeric cobalt(III) complexes of the type



point to the existence of substituent effects that suggest that an inner-sphere path may come into play when an α-C═O group is available for bridging. Specific rates (25 °C, 1.3 M $HClO_4$) have been found to be 0.43 M^{-1} s^{-1} for the μ-formato oxidant, 5.7 M^{-1} s^{-1} for μ-benzoylformato, and 94 M^{-1} s^{-1} for the μ-(4-methoxybenzoyl)formato complex. Moreover, the spectra of the reaction products from the accelerated oxidations indicate that the flavin ring has undergone some modifications (A.N.S., unpublished experiments, Kent State University, 1981).

(26) Values of k_{Ru} are taken from: (a) Endicott, J. F.; Taube, H. *J. Am. Chem. Soc.* **1964**, *86*, 1686. (b) Fan, F.-R. F.; Gould, E. S. *Inorg. Chem.* **1974**, *13*, 2647. These generally refer to reactions carried out in 0.1 M HCl, $\mu = 0.50$.

(27) Hua, L. H.-C.; Balahura, R. J.; Fanchiang, Y.-T.; Gould, E. S. *Inorg. Chem.* **1978**, *17*, 3692.