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The Role of Coordinated Sulfur in Oxidation–Reduction. I. The Chromium(II) Reduction of Mercaptoacetatobis(ethylenediamine)cobalt(III) and Its Glycollato Analog

Sir:

Recent research has revealed a widespread utilization of nonheme iron–sulfur proteins in biological oxidation–reduction processes.[1] Iron, acid-labile sulfur, and thiolate sulfur from cysteine are stoichiometrically and functionally related, implying coordination by sulfur.[1] Esr studies of isotopically substituted samples of a representative two-iron protein indicate that both iron atoms, both acid-labile sulfur atoms, and at least some of the cysteinyl sulfur participate in the redox site.[2] These developments serve to underscore the lack of quantitative information regarding the influence of coordinated thiolate functions on the rates and mechanisms of oxidation–reduction reactions. We wish to describe a markedly enhanced rate of inner-sphere reduction of a mononuclear cobalt(III) complex arising from replacement of a single coordinated alcoholate oxygen by thiolate sulfur. These represent the first studies of this type of the thiolate and alcoholate functions.

$[Co(en)_2OCH_2COO]ClO_4$ was prepared by a method analogous to that used for $[Co(en)_2(NH_2CH_2COO)]Cl_2$.[3a] Addition of aqueous sodium perchlorate to a solution of the initial product yielded the perchlorate salt which was recrystallized from water. *Anal.* Calcd: C, 20.45; H, 5.15; N, 15.9; Co, 16.7. Found: C, 20.36; H, 5.12; N, 15.7; Co, 16.6 (as $Co(tripyridine)_2^{2+}$ after liquid-fire (HNO_3–$HClO_4$) decomposition). Spectral data were (λ (ϵ): 5180 (132), 3600 Å (140) in water and 4990 (113), 3480 Å (121) in 0.10 *M* $HClO_4$. Intense infrared absorption (in KBr) at 1635 and 1360 cm^{-1} is characteristic of coordinated carboxylate.[3] The failure to incorporate H_2O on recrystallization together with spectral comparison with *cis*-$[Co^{III}(NH_3)_4(H_2O)(CH_3COO)](ClO_4)_3$ (λ (ϵ): 5100 (67), 3550 Å (50) in water)[4] provides assurance that the alcohol function remains coordinated for reasonable periods in acidic or neutral solution. The molar conductance is that expected for a uniunivalent electrolyte. Spectrophotometric and potentiometric titrations yielded an approximate pK_a of 3.0 for the complex at 1.0 *M* ionic strength and 25°.

$[Co(en)_2(SCH_2COO)]ClO_4$ was synthesized by a procedure similar to that used to produce $CrSH^{2+}$ in solution.[5] Cobalt(II) perchlorate, ethylenediamine, and the disulfide of mercaptoacetic acid react in 2:4:1 molar ratios in deaerated water to yield the desired compound which was recrystallized several times from water (λ 5160 Å (ϵ 149)). *Anal.* Calcd: S, 8.67; C, 19.5; H, 4.88; N, 15.2. Found: S, 8.53; C, 19.5; H, 4.84; N, 15.13. Infrared absorption (KBr) at 1635 and 1340 cm^{-1} is assigned to coordinated carboxylate, and the absence of S–H absorption at ~2500 cm^{-1} is indicative of thiolate coordination. This complex is not detectably basic under the conditions studied and, after allowing for the change in sulfur substituent from hydrogen to alkyl, seems comparable to $CrSH^{2+}$ in this sense.[5] No appreciable spectral change occurs between 10^{-7} and 1 *M* $HClO_4$. Further, when sufficient complex is brought into 0.1 *M* HCl solution (by reaction with equivalent $(C_6H_5)_4AsCl$ followed by centrifugation of $(C_6H_5)_4AsClO_4$) to be 0.1 *M* in complex, the pH is unchanged from its original value.

Reaction rates with chromium(II) were determined at 25° and 1.0 *M* ionic strength ($LiClO_4$–$HClO_4$) using a Durrum-Gibson stopped-flow spectrophotometer at the low-energy cobalt absorption peak. $Co(en)_2(HOCH_2COO)^{2+}$ is consumed under pseudo-first-order conditions according to the rate law, $(38 + 0.99[H_3O^+]^{-1})$-$[Cr(II)][Co(III)]$ (time in seconds), over the ranges $1.0 \times 10^{-2}\ M < [Cr(II)] < 5.0 \times 10^{-2}\ M$ and $1.0 \times 10^{-2}\ M < [H_3O^+] < 1.0 \times 10^{-1}\ M$. Elimination of the acid dissociation constant from the value for the inverse acid path yields $k_{O_2} = 990\ M^{-1}\ sec^{-1}$ for reaction of the deprotonated species.

$$Co(en)_2(OCH_2COO)^+ + Cr(II) \xrightarrow{k_{O_2}} \text{products} \qquad (1)$$

Chrominum(II) was found, by spectrophotometry, to consume $Co(en)_2(HOCH_2COO)^{2+}$ in a 1:1 molar ratio over a range of $[Co^{III}]:[Cr^{II}]$ from 0.5 to 2.5 at the 5×10^{-3} *M* level. The product spectrum excludes $Cr(H_2O)_6^{3+}$ as an appreciable product, indicating instead an inner-sphere reaction with the bridging glycollate ligand captured in the inert Cr(III) coordination sphere. A molecular model of the cobalt reactant indicates that the chelate link makes a doubly bridged reaction extremely unlikely for steric reasons. The similar rate constant in the acid-independent path to the *cis*-$Co(NH_3)_4(OAc)(H_2O)^{2+}$–Cr(II) reaction (see Table I), where $CrOAc^{2+}$ is the dominant product,[4c] and the spectral properties of the products[6] are consistent with carboxylate bridging for this path although an alcohol bridge has not yet been rigorously excluded. The inverse acid dependence and high rate constant for the second path virtually demand alkoxide bridging.

Reaction of Cr(II) with $Co(en)_2(SCH_2COO)^+$ at 0.1 *M* $HClO_4$ is complete at the lowest observable equimolar concentrations ($5 \times 10^{-5}\ M$) within the mixing "dead time" of our apparatus. We conservatively estimate $t_{1/2} < 0.010$ sec and, assuming a second-order reaction, calculate $k_{S_2} > 2 \times 10^6\ M^{-1}\ sec^{-1}$ (25°) for

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Table I. Rate of Reduction of Cobalt(III) Complexes by Chromium(II)[a]

	Complex	Rate, M^{-1} sec^{-1}	Ref
I.	$Co(NH_3)_5F^{2+}$	9×10^5	*b*
II.	$Co(NH_3)_5Cl^{2+}$	2.6×10^6	*b*
III.	$Co(NH_3)_5OH^{2+}$	1.7×10^6 [h]	*c*
IV.	$Co(NH_3)_5(OAc)^{2+}$	3.5×10^{-1}	*d*
V.	$Co(NH_3)_4(OAc)_2^+$	$15 + 50[H_3O^+]$	*e*
VI.	$Co(NH_3)_4(H_2O)(OAc)^{2+}$	$47 + 2.8[H_3O^+]^{-1}$	*e*
VII.	$Co(NH_3)_5(OOCCH_2OH)^{2+}$	3.1	*f*
VIII.	$Co(en)_2(HOCH_2COO)^{2+}$	38	*g*
IX.	$Co(en)_2(OCH_2COO)^+$	9.9×10^2	*g*
X.	$Co(en)_2(SCH_2COO)^+$	$>2 \times 10^6$	*g*

[a] $\mu = 1.0$ *M*, 25°. [b] Reference 9. [c] A. Zwickel and H. Taube, *J. Amer. Chem. Soc.*, **81**, 1288 (1959). [d] Reference 7b. [e] Reference 4a,c. [f] Reference 6. [g] This work. [h] At 20°, $\mu = 1.20$ *M*.

$$Co(en)_2(SCH_2COO)^+ + Cr(II) \xrightarrow{k_{S_2}} \text{products}$$

This reaction is also characterized by 1:1 stoichiometry (spectrally determined) yielding a red chromium(III) product which is indicative of a thiolate bridged reaction. Subsequent discussion will focus on the mechanistically comparable k_2 paths.

Table I summarizes our observations and relevant results from previous work on inner-sphere reductions. The glycollate complex appears unreactive relative to $Co(NH_3)_5OH^{2+}$. Steric hindrance of the alkoxide oxygen by the methylene group probably contributes substantially to this effect. A decreased stability of the precursor complex[7] is one likely consequence of the hindrance. We are studying the $Cr(II)$–$Co(NH_3)_5(HOCH_3)^{3+}$ [8] reaction to further evaluate the influence of alkoxide ligands.

The most significant reactivity influence evident in the results is that conferred by the thiolate ligand. The mercaptoacetate complex is more reactive toward reduction by Cr(II) than its oxygen analog by over three orders of magnitude. In spite of its potentially hindering methylene substituent, it approaches the highest reactivities observed for this class of reactants and may approach rate-limiting substitution on Cr(II).[7,9]

An important barrier to activation for the class of reactions under consideration is the apparent necessity, impressively supported experimentally,[10] to stretch the cobalt-bridging ligand bond prior to electron transfer.[11] A further influential factor may be the extent to which the ligand σ orbital overlaps the cobalt e_g orbital[11] although experimental evidence on this point is less convincing. The much greater reactivity which we have observed for the sulfur over the oxygen complex correlates nicely with a diminished steric hindrance of the larger thiolate sulfur by the methylene group and a lower bond strength and greater covalency expected for the cobalt–sulfur bond. The potential influences of the thermodynamic driving forces[7] and precursor complex stabilities[7] on the rate difference are difficult to assess at present except that the steric component of the latter influence should contribute in the observed direction.

Less dramatic effects than those we present have previously been reported for Co(III) complexes with ligands containing uncoordinated thio ether functions.[12] We are extending our studies to other reductants (particularly of the outer-sphere class), sulfur functions, and oxidizing centers.

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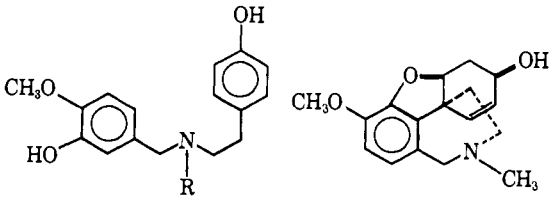
Intramolecular Oxidative Phenol Coupling. II. A Biogenetic-Type Synthesis of (±)-Maritidine[1]

Sir:

Radioactive tracer experiments have verified that most, and probably all, of the Amaryllidaceae alkaloids are biosynthesized by way of intramolecular oxidative coupling of either O-methylnorbelladine (**1**) or O,N-dimethylnorbelladine (**2**).[2] Although it has been recognized that execution of this scheme in the laboratory would provide an exceedingly simple synthetic route to these alkaloids,[3] Barton and Kirby's[4] synthesis of galanthamine (**3**) remains the only reported biogenetic-type synthesis of an Amaryllidaceae alkaloid; these



1, R = H
2, R = CH_3

3

workers were able to effect the intramolecular *ortho–para* coupling of **2** in 1.4% yield. We recently described a new method for carrying out intramolecular oxidative phenol coupling[1] and wish now to report its use in the biogenetic-type synthesis of (±)-maritidine

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