NMR line widths observed for the present series of compounds are uniformly broader in DMF than in the less viscous solvent MeCN.

The line widths for the ^{183}W ($I = {}^1/_2$) resonances for the limited range of binuclear and trinuclear tungsten species examined (Table IX) are rather difficult to measure accurately. The low sensitivity of the ^{183}W nucleus frequently means that only a limited number of data points define the signal after a reasonable data collection time (10–30 h for [W] = 0.5 M), and this leads to large uncertainties in line width measurement. However, the effect of the quadrupolar Cu nucleus on the ^{183}W NMR line widths (Hz) can be discerned as follows: $[WS_4]^{2-}$, <1; $[(CN)CuS_2WS_2]^{2-}$, ~5; $[(CN)CuS_2WS_2Cu(CN)]^{2-}$, ~60. Interpretation parallels that of the Mo derivatives discussed above.

Acknowledgment. The Australian Research Grants Scheme is thanked for generous support. S.F.G. thanks the Australian Wool Corp. for a research scholarship.

Registry No. $(n\text{-}Pr_4N)_2[(CN)CuS_2MoS_2]$, 86305-72-8; $(n\text{-}Pr_4N)_2[(CN)AgS_2MoS_2]$, 90790-31-1; $(n\text{-}Pr_4N)_2[(CN)CuS_2WS_2]$, 90790-29-7; $(n\text{-}Pr_4N)_2[(CN)AgS_2WS_2]$, 90790-27-5; $(Et_4N)_2[(CN)CuS_2MoS_2Cu(CN)]$, 90790-30-0; $(Ph_4As)_2[(CN)CuS_2MoS_2Cu(CN)]\cdot H_2O$, 90790-26-4; $(n\text{-}Pr_4N)_2[(CN)CuS_2MoS_2Cu(CN)]$, 86305-73-9; $(n\text{-}Pr_4N)_2[(CN)CuS_2WS_2Cu(CN)]$, 90790-33-3; $(Ph_4As)_2[(CN)CuS_2MoOS]$, 90790-35-5; $(Et_4N)_2[(CN)CuS_2MoOS]$, 90790-36-6; $(Et_4N)_2[(CN)CuS_2WOS]$, 90790-38-8; $(Ph_4P)_2[(CN)AgS_2MoS_2]$, 86430-75-3; $[MoO_4]^{2-}$, 14259-85-9; $[MoO_3S]^{2-}$, 25326-93-6; $[MoO_2S_2]^{2-}$, 16608-22-3; $[MoOS_3]^{2-}$, 19452-56-3; $[MoS_4]^{2-}$, 16330-92-0; $[MoO_3Se]^{2-}$, 90790-39-9; $[MoO_2Se_2]^{2-}$, 23507-81-5; $[MoOSe_3]^{2-}$, 39735-33-6; $[MoSe_4]^{2-}$, 21559-00-2; $[WO_4]^{2-}$, 14311-52-5; $[WO_3S]^{2-}$, 25326-94-7; $[WO_2S_2]^{2-}$, 16450-49-0; $[WOS_3]^{2-}$, 19452-55-2; $[WS_4]^{2-}$, 14916-78-0; ^{95}Mo, 14392-17-7; ^{183}W, 14265-81-7.

Supplementary Material Available: Listings of observed and calculated structure factors, anisotropic thermal parameters, and atomic coordinates and expanded listings of bond lengths and angles for I–III (Tables S1–S15) (88 pages). Ordering information is given on any current masthead page.

Contribution from the Department of Chemistry,
Baylor University, Waco, Texas 76798

Stoichiometry, Kinetics, and Mechanisms of the Chromium(VI) Oxidation of L-Cysteine at Neutral pH

DANIEL W. J. KWONG and DAVID E. PENNINGTON*

Received August 24, 1983

The stoichiometry, kinetics, and mechanisms of the chromium(VI) oxidation of L-cysteine at neutral pH have been studied. A 3:1 L-cysteine:Cr(VI) redox stoichiometry has been established, with L-cystine and Cr(L-cysteinato-$N,O,S)_2^-$ as the sole products. The rate law is of the form $-d[Cr(VI)]/dt = a[L\text{-}Cys]^2[Cr(VI)]/(1 + b[L\text{-}Cys])$, where $a = 140 \pm 13$ M^{-2} s^{-1} and $b = 220 \pm 25$ M^{-1} at 298 K, $I = 1.0$ M (Na^+), and pH 7.04 ± 0.02 (0.2 M $HC_2H_3O_2/NaC_2H_3O_2$). The temperature dependencies of a and b were evaluated in the range 15–35 °C. Four mechanisms are presented; however, the preferred one involves the initial formation of a chromate thio ester [$Q_1 = 220 \pm 25$ M^{-1} ($\Delta H_1 = -4 \pm 1.6$ kcal/mol, $\Delta S_1 = -1 \pm 6$ cal/(mol K))], a two-electron reduction of Cr(VI) with concomitant formation of L-cystine [$k_2 = 0.64 \pm 0.003$ M^{-1} s^{-1} ($\Delta H_2^{\ddagger} = 13 \pm 3.2$ kcal/mol, $\Delta S_2^{\ddagger} = -20 \pm 11$ cal/(mol K))], and follow-up steps to complete the stoichiometry. The results are compared with those of related studies of thiol oxidations by Cr(VI) in both acidic and neutral solutions.

Introduction

The oxidations of L-cysteine and related thiols by chromium(VI) in acidic solution have been studied by McCann and McAuley[1] and by McAuley and Olatunji.[2] Each of the oxidations is characterized by a preredox equilibrium involving the formation of a 1:1 thio ester of chromium(VI).[1,3] Both equilibrium spectrophotometric data and stopped-flow kinetic data support this mechanistic step. The rate laws for the redox processes are of the form

$$\frac{-d[Cr(VI)]}{dt} = \frac{(a[RSH] + b[H^+])[Cr(VI)][RSH]}{1 + c[RSH]} \quad (1)$$

and involve a redox stoichiometry of [RSH]:[Cr(VI)] = 3:1 with L-cysteine in substantial excess. A mechanism utilizing the formation of the thio ester species followed by competitive redox decomposition of the intermediate by reaction with either H^+ or RSH was postulated to accommodate the rate law. At least two products of chromium(III) were formed in the case of L-cysteine: the first, presumably $Cr(H_2O)_4$(L-cystine-$N,O)^{3+}$, in ~60% yield and a more highly charged (≥4+) species in ~40% yield.

By contrast, two preliminary kinetic studies[4,5] on the oxidations of L-cysteine and other thiols at or near neutral pH indicate a simple, mixed second-order rate law. The redox stoichiometry for the oxidation of D-penicillamine[4] remains 3:1; however, the sole chromium(III) product, Cr(D-penicillaminato-$N,O,S)_2^-$, is radically different from that reported for the L-cysteine oxidation in acidic solution. A crystal structure of the closely related species Na[Cr(L-cysteinato-$N,O,S)_2]\cdot 2H_2O$ has been reported,[6] where the amino acidato groups are facially coordinated with trans sulfurs and cis nitrogens and oxygens.

In the present work a detailed kinetic and stoichiometric investigation of the oxidation of L-cysteine by chromium(VI) at neutral pH is reported.[7]

Experimental Section

Reagents. Sodium chromate and L-cysteine were used as received from Fisher Scientific Co. and U.S. Biochemical Corp., respectively. Sodium perchlorate solutions were prepared by neutralization of an aliquot of standard perchloric acid (70% Sargent-Welch) with anhydrous sodium carbonate (Mallinckrodt, AR) and diluted to volume with doubly distilled water. Solutions of perchloric acid were prepared by dilution of the stock acid with doubly distilled water. Sodium acetate (Mallinckrodt, AR) and glacial acetic acid (Du Pont, Electronic grade) were used to prepare buffer solutions to pH 7.02–7.06. Na[Cr(L-cysteinato-$N,O,S)_2]\cdot 2H_2O$ was prepared by the method of ref 6. Doubly distilled water was prepared from deionized tap water by distillation first from alkaline permanganate solution and then from

(1) McCann, J. P.; McAuley, A. *J. Chem. Soc. Dalton Trans.* **1975**, 783.
(2) McAuley, A.; Olatunji, M. A. *Can. J. Chem.* **1977**, *55*, 3335.
(3) McAuley, A.; Olatunji, M. A. *Can. J. Chem.* **1977**, *55*, 3328.
(4) Hojo, Y.; Sugiura, Y.; Tanaka, H. *J. Inorg. Nucl. Chem.* **1977**, *39*, 1859.
(5) Connett, P. H.; Wetterhahn, K. E. *Struct. Bonding (Berlin)*, in press.
(6) De Meester, P. Hodgson, D. J.; Freeman, H. C.; Moore, C. J. *Inorg. Chem.* **1977**, *16*, 494.
(7) The present study was well underway when a preprint of the preliminary report[5] was graciously shared by Dr. Wetterhahn.

0020-1669/84/1323-2528$01.50/0

dilute sulfuric acid solution and stored in Pyrex bottles. Sephadex C-25 and A-25 resins were used as received.

Stoichiometry. Sodium chromate and L-cysteine, each mixed in a buffer of sodium acetate/acetic acid at pH 7.02–7.06 and I = 1.0 M ($NaClO_4$), were mixed and allowed to react for at least 10 half-lives. The solutions were diluted and charged onto Sephadex A-25 resins. (Sephadex C-25 resins were also employed in early runs to test for the presence of any cationic species.) Solutions of Cr(L-cysteinato-$N,O,S)_2^-$ were eluted with 1% (by weight) sodium chloride solution.[8] The chromium(III) product was identified by its ion-exchange behavior, its visible/UV absorption spectrum [λ_{max}, nm (ϵ, M^{-1} cm^{-1}): 605 (87.3), 540 (64.5) sh, 410 (81.7), 257 (10000) authentic sample:[6] 605 (88.0), 540 (66.7) sh, 410 (86.7), 257 (9840)], and a total chromium assay.[9] The L-cystine product was identified only qualitatively by its melting point, 257 °C dec (lit.[10] mp 258–261 °C dec), and an IR spectrum (which compared band for band with that of an authentic sample of L-cystine). The redox molar stoichiometry, L-cysteine:Cr(VI), was determined by spectrophotometric titrations at 372 nm after the method of Hojo, Sugiura, and Tanaka.[4]

Kinetics. Kinetic studies were conducted by monitoring the absorbance of the chromate ion at 372 nm vs. time under pseudo-first-order conditions of excess L-cysteine. In a typical experiment, freshly prepared L-cysteine stock solution [in a 0.2 M $NaC_2H_3O_2$/$HC_2H_3O_2$ buffer of pH 7.02–7.06 and I = 1.0 M ($NaClO_4$)] and the buffer were pipetted into a 5.00-cm spectrophotometer cell. The cell was thermostated to the appropriate reaction temperature, and a small, thermostated volume of Na_2CrO_4/buffer stock solution was injected into the reaction cell via a hypodermic syringe. The cell was then stoppered, shaken, and returned to the sample compartment of a Cary 14 recording spectrophotometer for continuous measurements of absorbance vs. time. The temperature at the end of each run was monitored in the cell by a thermistor probe connected to a Thinc Model Tm-701 thermistor. After it was ascertained graphically that first-order plots of ln ($A_t - A_\infty$) vs. time were consistently linear for at least 3 half-lives, the data were all analyzed by utilizing a nonlinear least-squares program, where k_{obsd} and A_∞ were "best-fit" values of the pseudo-first-order rate coefficient and infinite-time absorbance, respectively.

Measurements. Visible/UV spectra and kinetics were recorded on a Cary Model 14 recording spectrophotometer equipped with a thermostated cell holder, which in turn was connected to a Forma circulating, constant-temperature water bath. IR spectra were recorded on a Perkin-Elmer Model 1320 infrared spectrophotometer. All pH measurements were made on a Beckman Model Century SS pH meter using a combination electrode.

Results and Discussion

Stoichiometry. The results of experiments performed to establish the redox stoichiometry of the chromium(VI) oxidation of L-cysteine at neutral pH are shown in Figure 1. On the basis of the break in absorbance at 372 nm the molar ratio is L-cysteine: Cr(VI) = 3:1. Additionally, Cr(L-cysteinato-$N,O,S)_2^-$ was found to be the sole chromium(III) product, and L-cystine was identified as the oxidation product (vide infra). Thus, the formal, overall reaction stoichiometry is given by eq 2. The four L-cysteines over and above the redox stoi-

$$2HCrO_4^- + 10\text{L-}^-O_2CCH(^+NH_3)CH_2SH = 2Cr[\text{L-}O_2CCH(NH_2)CH_2S]_2^- + 3(\text{L-}^-O_2CCH(^+NH_3)CH_2S\text{-})_2 + 8H_2O \quad (2)$$

chiometry are required to account for the observed ligation of the chromium(III) product. The observed redox stoichiometry is the same as that reported by McCann and McAuley[1] for the same reactants in acidic solution and that reported by Hojo, Sugiura, and Tanaka[4] for the Cr(VI) oxidation of D-penicillamine at neutral pH. Furthermore, the chromium(III) product, Cr(L-cysteinato-$N,O,S)_2^-$, observed in the present study is quite analogous to the Cr(D-penicillaminato-$N,O,S)_2^-$ ion reported by the latter authors. Given the close agreement (vide infra) of both visible and ultraviolet spectral maxima and intensities between the observed product and those of an independently prepared and structural characterized isomer,[6] the chromium(III) product is very probably the cis(N),cis(O),trans(S) isomer of the Cr(L-cysteinato-$N,O,S)_2^-$ ion. However, spectral data on the other two facially coordinated, geometric isomers of this ion are lacking, thereby precluding an unequivocal product identification. Interestingly, product identification in the reactions of Cr(VI) with various one- and two-electron substrates led Cooper, Staudt, Smalser, Settzo, and Haight[11] to conclude that initial one-electron reduction of Cr(VI) leads to Cr(III) entrapment of oxidized substrate whereas initial two-electron reduction leads to Cr(III) entrapment of excess substrate. If this generalization were accepted, then the observation of Cr(L-cysteinato-$N,O,S)_2^-$ as product herein would imply an initial two-electron reduction of Cr(VI) by L-cysteine at neutral pH. In acidic solution the reported product is $Cr(H_2O)_4$(L-cystine-$N,O)^{3+}$, and a one-electron initiation step is implied. Alternatively, the observation of different products, $Cr(H_2O)_4$(L-cystine-$N,O)^{3+}$ in acidic solution vs. Cr(L-cysteinato-$N,O,S)_2^-$ at neutral pH, may simply hinge on the acid lability of the Cr–S bonds. For example, Agent has found[12] that the structurally characterized isomer[6] of the Cr(L-cysteinato-$N,O,S)_2^-$ ion undergoes sequential acid hydrolyses of the two chromium–sulfur bonds.

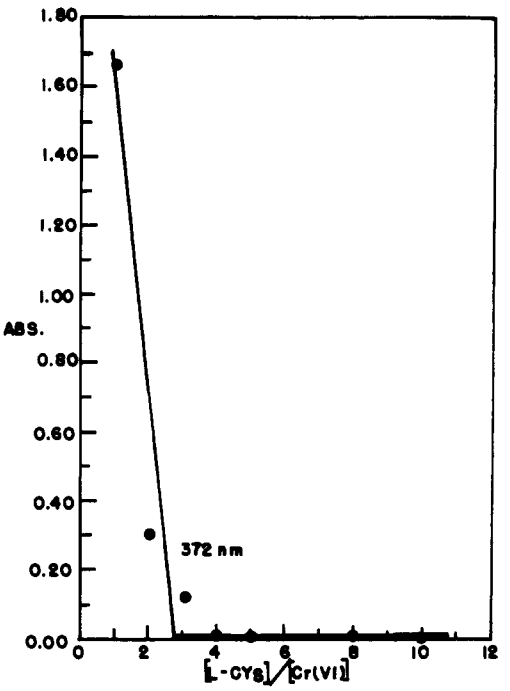

Figure 1. Spectrophotometric redox titration of L-cysteine and Cr(VI) at neutral pH.

Kinetics. L-Cysteine is present in to 50–500-fold molar excess, ensuring pseudo-first-order kinetic conditions at pH 7.04 (0.2 M $HC_2H_3O_2/NaC_2H_3O_2$ buffer) and at I = 1.0 M ($NaClO_4$). Treatment of the kinetic data was accomplished via a nonlinear least-squares program designed to fit the absorbance vs. time data to a single exponential function of the form $A_t = (A_0 - A_\infty)\exp(-k_{obsd}t) + A_\infty$, where k_{obsd}, A_0, and A_∞ are adjustable parameters. In all cases the absorbance A_t calculated from the above equation by using the adjusted

(8) Grouhi-Witte, G.; Weiss, E. *Z. Naturforsch., B: Anorg. Chem., Org. Chem.* **1976**, *31B*, 1190.
(9) Haupt, G. W. *J. Res. Natl. Bur. Stand. (U.S.)* **1952**, *48*, 414.
(10) "Handbook of Chemistry and Physics", 14th ed.; Chemical Rubber Publishing Co.: Cleveland, OH, 1959; p 948.
(11) Cooper, J. N.; Staudt, G. E.; Smalser, M. L.; Settzo, L. M.; Haight, G. P. *Inorg. Chem.* **1973**, *12*, 2075.
(12) Agent, C. L.; Pennington, D. E. "Abstracts of Papers", 34th Southwest Regional Meeting of the American Chemical Society, Corpus Christi, TX, 1978; American Chemical Society: Washington, DC, 1978; INOR 23.

Table I. Pseudo-First-Order Rate Coefficients for the Oxidation of L-Cysteine by Chromium(VI) at Neutral pH[a]

15.4 °C[b]		24.9 °C[b]		34.5 °C[b]	
$10^3 \times$ [L-Cys], M	$10^3 k_{obsd}$, s^{-1}	$10^3 \times$ [L-Cys], M	$10^3 k_{obsd}$, s^{-1}	$10^3 \times$ [L-Cys], M	$10^3 k_{obsd}$, s^{-1}
2.13	0.277[c]	2.18	0.489	2.10	0.834[c]
4.32	0.804[d]	2.25	0.490	4.42	2.56[d]
6.68	1.35[d]	4.31	1.55[e]	6.62	4.49[c]
8.72	1.83[d]	4.38	1.35	8.72	6.81
8.80	1.98	4.48	1.26	8.80	6.51
13.2	3.15[d]	6.58	2.60[d]	13.2	12.1[c]
17.6	4.50[d]	8.67	3.90[d]	17.7	17.7[c]
17.6	3.93[c]	8.79	3.37	22.1	23.0[d]
17.8	4.02	13.1	6.57[f]		
22.0	6.23[d]	13.1	6.49[c]		
22.1	5.95	13.3	6.64[g]		
		17.5	9.26[d]		
		21.8	12.8[f]		
		21.9	12.4[c]		
		22.0	10.9		

[a] At $I = 1.0$ M ($NaClO_4$); 0.2 M $NaC_2H_3O_2/HC_2H_3O_2$ buffer at pH 7.04 ± 0.02; [Cr(VI)] = 4.39×10^{-5} M except as noted. [b] ±0.2 °C. [c] Average of triplicate runs. [d] Average of duplicate runs. [e] 10^5[Cr(VI)] = 2.22 M. [f] 10^5[Cr(VI)] = 8.79 M. [g] 10^5[Cr(VI)] = 1.77 M.

parameters consistently agreed with the measured absorbances within 1%, never deviating by more than 2%. The k_{obsd} values so derived are given in Table I for each of three temperatures: 15.5, 24.9, and 34.5 °C. An examination of entries 3 and 4, 9 and 10, 11 and 10 in column 4 reveals that k_{obsd} at 24.9 °C is relatively independent of [Cr(VI)] as would be expected on the basis of a rate law $-d(\ln [Cr(VI)])/dt = k_{obsd}$, where $k_{obsd} = f([L\text{-Cys}])$. It was *assumed* that similar behavior obtained at the other temperatures. Although it is evident from the data (cf. columns 1 and 2, 3 and 4, and 4 and 5 in Table I) that the dependence of k_{obsd} upon [L-cysteine] is somewhat greater than 1, two preliminary sets of results on Cr(VI) oxidations of thiols at or near neutral pH had indicated an essentially first-order dependence of k_{obsd} upon [L-cysteine].[4,5] Hence, a function of the type $k_{obsd} = a + b[L\text{-Cys}]$ was tried first. A linear least-squares fit of the data, e.g., at 24.9 °C, yielded values of $a = (-1.24 \pm 0.20) \times 10^{-3}$ s^{-1} and $b = 0.599 \pm 0.015$ M^{-1}/s^{-1} at pH 7.03, where the errors are standard errors[13] in the slope and intercept, respectively. While the function is linear except for a badly deviant point at low [L-cysteine] and even gives a rate coefficient comparable to the simple, mixed second-order rate coefficients (both preliminary) reported earlier,[4,5] a fatal blow for this simple function is the negative value derived for the intercept. The error in the intercept is not large enough to compensate for the negative value, and a negative rate coefficient has no rational interpretation. Entirely similar results were obtained at the other two temperatures.

Since a plot of k_{obsd} vs. [L-cysteine]^2 exhibited rate saturation at high [L-cysteine], a functional dependence of k_{obsd} on [L-cysteine] analogous to that proposed by McCann and McAuley[1] was adopted. The rate law is of the form

$$\frac{-d[Cr(VI)]}{dt} = \frac{a[L\text{-Cys}]^2[Cr(VI)]}{1 + b[L\text{-Cys}]} \quad (3)$$

In fact, the form of the rate law is a special case of eq 1 with the assumption that the $[H^+]$-dependent path is negligible at neutral pH. Thus eq 4 can be cast in a linear form of slope $= b/a$ and intercept $= 1/a$.

$$k_{obsd} = a[L\text{-Cys}]^2/(1 + b[L\text{-Cys}]) \quad (4)$$

Table II. Rate Coefficients Derived from the Dependence of k_{obsd} on [L-Cys][a]

t,[b] °C	a,[c] M^{-2} s^{-1}	b,[c] M^{-1}	ref
15.5	76 ± 6.4	250 ± 25	*d*
24.9	140 ± 13	220 ± 25	*d*
34.5	220 ± 14	170 ± 15	*d*
15.0	8 ± 2[e]	1280 ± 160	1
25.0	12 ± 5[e]	1030 ± 110	1
35.0	20 ± 5[e]	760 ± 60	1

[a] At $I = 1.0$ M ($NaClO_4$), at pH 7.04 ± 0.02 (0.2 M $NaC_2H_3O_2/HC_2H_3O_2$) in this work; $[H^+] = 0.02$–1.00 M in ref 1. [b] ±0.02 °C. [c] Calculated from eq 4 in this work (see text). [d] This work. [e] Defined as k_2K_1 in ref 1; errors estimated from errors in k_2 and K_2.

Although *linear* data fits are given in Figure 2, final data refinement was accomplished via the *nonlinear* least-squares program using eq 4 with a and b as adjustable parameters. In Table II are presented the results of the final refinement of the parameters a and b, along the corresponding parameters of McCann and McAuley[1] for acidic solution. The values of a are seen (column 2) to increase with increasing temperature as do those in acidic solution whereas b is seen (column 3) to decrease with increasing temperature parallel to the acidic solution results. Various interpretations of these constants are presented in the following mechanisms. At least four mechanisms can be formulated to accommodate the full rate law given by eq 3.

Mechanism A. This mechanism is shown in eq 5–7, where the thio ester I is assumed to be in rapid equilibrium with the reactants, $Q_1 = k_1/k_{-1}$, and its reaction with a second L-cysteine is assumed to be rate-determining. On the basis of this

$$HCrO_4^- + \text{L-CysSH} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \underset{\text{I}}{\text{L-CysSCrO}_3^-} + H_2O \quad (5)$$

$$\text{I} + \text{L-CysSH} \xrightarrow{k_2} \text{L-cystine} + HCrO_3^- \quad (6)$$

$$HCrO_3^- + HCrO_4^- + 8\text{L-CysSH} = 2Cr(\text{L-Cys-}N,O,S)_2^- + 2\text{L-cystine} + 7\ H_2O \quad (7)$$

interpretation, the empirical constants a and b are readily shown to be $a = k_2Q_1$ and $b = Q_1$; thus $k_2 = 0.64 \pm 0.13$ M^{-1} s^{-1} and $Q_1 = 220 \pm 25$ M^{-1} at 298 K, $I = 1.0$ M (Na^+), and pH 7.03 ($HC_2H_3O_2/NaC_2H_3O_2$). A comparison of the value of k_2 with that observed (0.012 ± 0.003 M^{-1} s^{-1})[1] between pH 1.00 and 1.70 reveals that I reacts about 50-fold more rapidly in neutral solution. By contrast Q_1 in neutral solution is about a factor of 5 *smaller* than that observed (1030 ± 110 M^{-1})[1] in acidic solution. According to the interpretation of mechanism A (and mechanism B to follow), the rate-determining step is a two-electron-transfer process for Cr(VI) to Cr(IV). A more detailed treatment of this point is given later. Only for mechanism A is it possible to utilize fully the temperature dependencies of a and b. (For the alternative mechanisms presented below, a and b represent composite quantities that are only amenable to resolution for k_1 in mechanism B.) Plots of ln b and ln (a/bT) vs. $1/T$ yielded values of $\Delta H_1 = -4 \pm 1.6$ kcal/mol and $\Delta H_2^{\ddagger} = 13 \pm 3.2$ kcal/mol, respectively. Values of $\Delta S_1 = -1 \pm 6$ cal/(mol K) and $\Delta S_2^{\ddagger} = -20 \pm 11$ cal/(mol K) were calculated at 298 K from the standard thermodynamic relationships ($\Delta G = -RT \ln Q$ and $\Delta G = \Delta H - T\Delta S$) and the Eyring equation,[14] respectively. These results, along with those of other related thiols, are summarized in Table III. Unfortunately, the rather large errors for the

(13) Squires, G. L. "Practical Physics"; McGraw-Hill: New York, 1968; Chapter 4.

(14) Moore, W. J. "Physical Chemistry", 3rd ed.; Prentice-Hall: Englewood Cliffs, NJ, 1962; p 297.

Table III. Comparison of Formation Quotients, Redox Rate Constants, and Associated Temperature-Dependent Parameters for Chromate Thio Esters

oxidant	Q_1,[a] M	ΔH_1, kcal/mol	ΔS_1,[a] cal/(mol K)	$10^2 k_2$,[a] M^{-1} s^{-1}	$\Delta H_2^{\ddagger}$, kcal/mol	$\Delta S_2^{\ddagger}$,[a] cal/(mol K)	ref
L-cysteine	1030 ± 110	−5.0 ± 0.5	−3 ± 2	1.2 ± 0.3	10.8 ± 0.8	−27 ± 3	1
L-cysteine	220 ± 25	−4 ± 0.6	−1 ± 6	64 ± 13	13 ± 3.2	−20 ± 11	*b*
DL-penicillamine	700 ± 40	−6.8 ± 0.6	−10 ± 5	14.3 ± 1.0	9 ± 2	−33 ± 6	2, 3
glutathione	1440 ± 50	−4.5 ± 1.2	−1 ± 2	12.1 ± 0.4	7 ± 2	−40 ± 5	2, 3
β-mercaptoethylamine	1300 ± 100	−3.7 ± 1.5	2 ± 2				

[a] For $I = 1.0$ M (Na^+), 298 K. [b] This work.

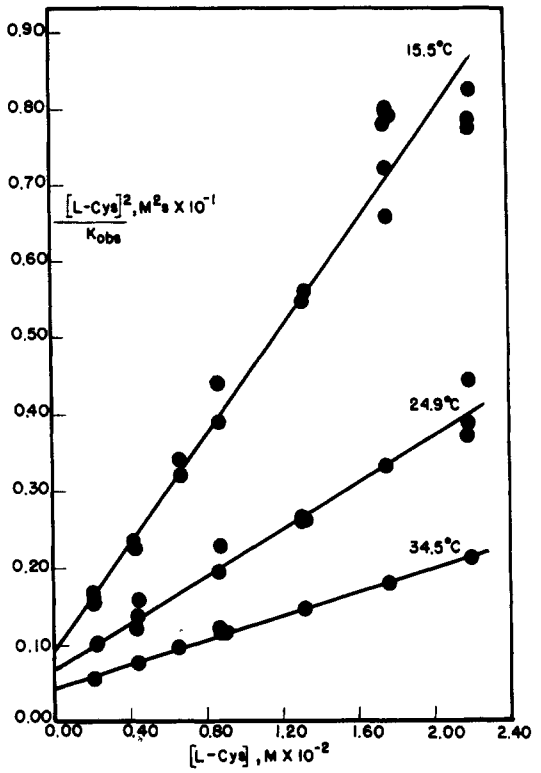

Figure 2. Linear least-squares fits of k_{obsd} as f([L-Cys]) for the oxidation of L-cysteine by Cr(VI) at neutral pH at 15, 25, and 35 °C.

temperature-dependent parameters derived herein make them equivalent (within experimental uncertanties) to those derived in acidic solution. If the mechanistic interpretations are correct, it is noteworthy that no differences in $\Delta H^{\ddagger}$ nor $\Delta S^{\ddagger}$ are discernible for one- vs. two-electron transfers.

Mechanism B. Equations 5–7 also constitute mechanism B, but the intermediate I is now taken to be at steady-state rather than at equilibrium.[15] Applying the steady-state approximation to I, one obtains $a = k_1k_2/k_{-1}$ and $b = k_2/k_{-1}$, from which $k_1 = 0.64 \pm 0.13$ M^{-1} s^{-1} (a/b) can be extracted. The remainder of the terms are composite quantities. The same activation parameters derived from k_2 in mechanism A are now ascribed to k_1 in mechanism B. Thus, $\Delta H_1^{\ddagger} = 13 \pm 3.2$ kcal/mol and $\Delta S_1^{\ddagger} = -20 \pm 11$ cal/(mol K). The value for k_1 above compares favorably with the k_f value of 2 ± 1 M^{-1} s^{-1} reported by McCann and McAuley[1] for the formation of I in acidic media. Unfortunately, no activation parameters were reported for k_f, which represents a minor path compared to that represented by $k_f[H^+]$ in acidic media.

While the following two mechanisms are less probable due to the requirement of a second intermediate, they are briefly presented for completeness.

(15) The authors are indebted to P. H. Connett and K. E. Wetterhahn (Cornell University) for suggesting the steady-state nature of I.

Mechanism C. Mechanism C consists of eq 5, 8, 6, and 7, where eq 8 represents the formation of a "dead-end" intermediate in rapid equilibrium with I. The empirical constants

$$\mathrm{I} \underset{k_{-1'}}{\overset{k_{1'}}{\rightleftharpoons}} \underset{\mathrm{II}}{*(\text{L-CysS})\mathrm{CrO_3^-}} \qquad (8)$$

$a = k_2Q_1$ and $b = (Q_1 + Q_1Q)$ may be derived from mechanism C, where $Q_1 = k_1/k_{-1}$ and $Q = k_1'/k_{-1}'$.

Mechanism D. Mechanism D is comprised of eq 5, 8, 9, and 7, where II is now assumed to be some "activated" form (perhaps of distorted geometry or expanded coordination number due to chelation of Cr(VI) by L-cysteine) of I.

$$\mathrm{II} + \text{L-CysSH} \xrightarrow{k_3} \mathrm{HCrO_3^-} + \text{L-cystine} \qquad (9)$$

Of the four mechanisms presented, mechanisms A and B are favored over mechanisms C and D due to (1) their inherent simplicity, (2) the implication of an intermediate in the form of the observed rate law, and (3) the previous detection[1] of a simple intermediate for the same reaction in an acidic medium. The formation of chromate(VI)–thio ester species is quite well documented, with the preponderance of data indicating their equilibrium formation. However, in the absence of direct evidence for even one intermediate in neutral solution, either equilibrium or steady-state formation of I is possible.

At first glance it would appear that mechanism A is essentially that given by McCann and McAuley[1] for the title reaction in acidic solution. There the intermediate chromate thio ester (I′, where I′ = HI) was proposed to be in equilibrium with reactants. Since $K_1 = 1050$ M^{-1}, a sustantial fraction of the reactant Cr(VI) is diverted to I′ at equilibrium, as is proposed for I in mechanism A. However, the dominant redox pathway is by reaction of I′ with H^+, presumably via a one-electron-transfer event. At least the stoichiometric observation, entrapment of oxidized substrate, supports the one-electron interpretation of their results. The pathway second order in [L-Cys] represents only a minor contribution to the overall disappearance of Cr(VI) in acidic solution whereas in neutral solution the corresponding pathway is dominant.

Returning now to the question of one- vs. two-electron transfer for the rate-determining step, the given mechanisms all reflect the two-electron interpretation. Three lines of evidence, albeit mostly negative, will be presented to address this point. Several sets of scavenger experiments were conducted in an attempt to intercept intermediate oxidation states of chromium. First, iodide ion was employed and was found to be without effect up to [I^-]:[L-cysteine] < 5. However, when the ratio ranged from 5 to 47, a modest decrease (21% at the highest ratio) in rate was observed. Since all of these experiments were conducted at the lowest [L-cysteine], it was concluded that at best Cr(V) is a minor intermediate in the scavenger experiments and that an insignificant amount of Cr(V) is formed in the majority of experiments reported herein. Second, EPR evidence for Cr(V), a d^1 ion, was sought under conditions of $[Cr(VI)]_0$ ranging from the kinetic conditions upward by a factor of 100 by utilizing both rapid manual mixing and slow diffusion of the Cr(VI) into the reaction mixture. *No* EPR signals were detected.[16] Third, efforts to

intercept Cr(IV) have been partially successful. Manganese(II), a known Cr(IV) scavenger,[17] was found to increase the rate of the Cr(VI)-L-cysteine reaction.[18] The increase in rate due to Mn(II) can be rationalized if, as seems likely, the Mn species produced were to react with Cr(VI). Thus, the above experiments point toward a two-electron process, a result that is at least consistent with the earlier inference from the stoichiometric results; however, they do not unequivocally preclude the participation of Cr(V) even though no direct or indirect evidence supports its involvement.

(16) The authors wish to thank Drs. William B. Smith and Christopher Saint of Texas Christian University for assistance with the EPR measurements.
(17) See, e.g.: Watanabe, W.; Westheimer, F. H. *J. Chem. Phys.* **1949**, *17*, 61.
(18) A detailed account of these experiments is to be submitted for publication.

Concluding Remarks

The rate law for the Cr(VI)-L-cysteine reaction at neutral pH has been established as a special case of the more general rate law for the reaction in acidic media, and the redox stoichiometry was found to be 3:1 L-Cys:Cr(VI). By contrast, however, the Cr(III) product observed in neutral solution is radically different from that in acidic solution. These results have been interpreted in terms of several mechanisms featuring two-electron-transfer steps in the rate-determining processes.

Acknowledgment. The authors are grateful to the Robert A. Welch Foundation for financial support of this research, to the National Science Foundation (Grant No. GP8248) for matching funds for purchase of the spectrophotometer, to Baylor University for a sabbatical leave, and to Charles Lok for assistance with computer programming.

Registry No. Cr, 7440-47-3; L-cysteine, 52-90-4.

Contribution from the Department of Chemistry, University of Virginia, Charlottesville, Virginia 22901

Reexamination of a Cytochrome Oxidase Model. A Noncoupled Iron-Copper Binuclear Complex

GREG A. BREWER and EKK SINN*

Received February 14, 1984

A heterobinuclear complex $[Fe(mac)(Bpm)Cu(acac)_2]^{2+}$ (I) (mac = the macrocyclic adduct of 2,6-diacetylpyridine and hydrazine; Bpm = bipyrimidine), previously postulated to contain a Fe(Bpm)Cu bridge, had been studied as a possible model for cytochrome oxidase. Four important questions arise with this complex. (1) The high-spin state of the Fe(II) conflicts with reports of low-spin Fe(II) in closely analogous environments. Our study removes the discrepancy: the complexes are all low spin except in adducts with $M(acac)_2$. (2) Can mac bend enough to permit coordination of the cis Bpm nitrogens, given that the only reported structural evidence is for planar mac? Our structure of $[Fe(mac)bpy](ClO_4)_2$ demonstrates appropriate mac bending, though not quite in the way that had been proposed. (3) $Cu(acac)_2$ is fairly resistant to the addition of an extra donor atom, and even more resistant to two donors as required for Bpm, and the observed magnetic properties can be explained by ligand-exchange reactions. We have eliminated this possibility with FAB mass spectral data. (4) The unpaired electrons of Cu and Fe appear to be coupled in I. To check whether a peculiarity of Bpm sometimes prevents electron coupling, we demonstrate the generality of coupling through M(Bpm)M bridges with M = Ni, Co, and Mn. Thus, binuclear complexes of Cu, Ni, Co, and Mn are now known to be antiferromagnetic, the first finding that fails to support a CuBpmFe bridge. A further experiment virtually eliminates the possibility of a Bpm bridge. Electronic spectra indicate the formation, from $[Fe(mac)bpy]^{2+}$, that Bpm is not necessary to form the binuclear complex. Possible mechanisms for the binucleation involve hydrogen bonding or, more likely, one of the uncoordinated mac N atoms, in which light the electrochemistry of the complex can now be reexamined. Crystal data for $[Fe(mac)(Bpm)Cu(acac)_2](ClO_4)_2$: $FeCl_2O_8N_8C_{28}H_{28}$, $P2_1/n$, $Z = 4$, $a = 8.943$ (3) Å, $b = 24.332$ (8) Å, $c = 15.954$ (5) Å, $\beta = 100.77$ (4)°.

Introduction

Since the first report of magnetic coupling in heterobinuclear and heterotrinuclear complexes,[1] there has been steadily increasing interest in such compounds.[2-10] One kind of bridge between dissimilar metal atoms, imidazolate (Im^-), is of interest because of the existence of such a bridge in bovine superoxide dismutase[11] and the postulate of a Cu-Im-Fe bridge in cytochrome *c* oxidase.[12-14] In the latter case, the iron is in a heme environment. To simulate this, a model compound was devised[14] with iron(II) bonded to the conjugated N_4 tetradentate mac[15] (Figure 1), which, from the perspective

(1) Gruber, S. J.; Harris, C. M.; Sinn, E. *Inorg. Nucl. Chem. Lett.* **1967**, *3*, 495.
(2) Gruber, S. J.; Harris, C. M.; Sinn, E. *Inorg. Chem.* **1968**, *7*, 268.
(3) Gruber, S. J.; Harris, C. M.; Sinn, E. *J. Chem. Phys.* **1968**, *49*, 2183.
(4) Sinn, E.; Harris, C. M. *Coord. Chem. Rev.* **1969**, *4*, 391 and references cited.
(5) Kokot, S.; Harris, C. M.; Sinn, E. *Aust. J. Chem.* **1972**, *25*, 45.
(6) O'Bryan, N. B.; Maier, T. O.; Paul, I. C.; Drago, R. S. *J. Am. Chem. Soc.* **1973**, *95*, 6640.
(7) O'Connor, C. J.; Freyberg, D. P.; Sinn, E. *Inorg. Chem.* **1979**, *18*, 1077.
(8) Mikuriya, M.; Okawa, H.; Kida, S.; Ueda, I. *Bull. Chem. Soc. Jpn.* **1978**, *50*, 2920.
(9) Brewer, G. A.; Petty, R. H.; Wilson, L. J.; Sinn, E. "Abstracts of Papers", 183rd National Meeting of the American Chemical Society, Las Vegas, NV, March 1982; American Chemical Society: Washington, DC, 1982.
(10) Banci, L.; Bencini, A.; Benelli, C.; Gatteschi, D. *Inorg. Chem.* **1982**, *21*, 3868 and references cited.
(11) Coughlin, P. K.; Dewan, J. C.; Lippard, S. J.; Watanabe, E.; Lehn, J.-M. *J. Am. Chem. Soc.* **1979**, *101*, 265.
(12) Palmer, G.; Babcock, G. T.; Vickery, L. E. *Proc. Natl. Acad. Sci. U.S.A.* **1976**, *73*, 2206.
(13) Tweedle, M. F.; Wilson, L. J.; Garcia-Iniguez, L.; Babcock, G. T.; Palmer, G. *J. Biol. Chem.* **1978**, *252*, 8065.
(14) Petty, R. H.; Welch, B.; Wilson, L.; Bottomley, L.; Kaddish, L. *J. Am. Chem. Soc.* **1980**, *102*, 611.
(15) Goedken, V. L.; Pork, Y.; Peng, S.; Norris, J. *J. Am. Chem. So.* **1974**, *96*, 7693.

0020-1669/84/1323-2532$01.50/0