13422 *J. Am. Chem. Soc.* **1998,** *120,* 13422−13428

Kinetics and Mechanism of the Oxidation of 10-Methyl-9,10-dihydroacridine by Chromium(VI,V,IV): Electron vs Hydrogen Atom vs Hydride Transfer

Oleg Pestovsky, Andreja Bakac,* and James H. Espenson*

Contribution from the Ames Laboratory and Department of Chemistry, Iowa State University,
Ames, Iowa 50011

Received July 6, 1998

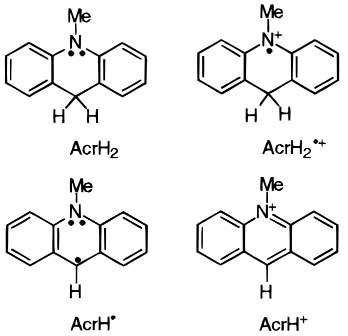
Abstract: The oxidation of $AcrH_2$ to $AcrH^+$ by hydrogen chromate ions in H_2O/MeCN (4:1, v/v) is a chain reaction that is strongly inhibited by oxygen. The initiation reaction between $AcrH_2$ (or $AcrD_2$) and H_2CrO_4 forms $AcrH_2^{\bullet+}$ (or $AcrD_2^{\bullet+}$) and occurs by a one-electron mechanism, $k^H = k^D = 4.6 \times 10^2$ L mol^{-1} s^{-1} (25 °C). The Cr(V) produced along with $AcrH^\bullet$ (from the acid ionization of $AcrH_2^{\bullet+}$) are chain-carrying intermediates. The propagating reaction between $AcrH_2$ and Cr(V), $k = 1 \times 10^8$ L mol^{-1} s^{-1}, is of key importance since it is a branching reaction that yields two chain carriers, $AcrH^\bullet$ and CrO^{2+}, by hydrogen atom abstraction. The same partners react competitively by hydride ion abstraction, to yield Cr^{3+} and $AcrH^+$, $k = 1.2 \times 10^7$ L mol^{-1} s^{-1}, in the principal termination step. The reaction of CrO^{2+} and $AcrH_2$, $k^H = 1.0 \times 10^4$ and $k^D = 4.8 \times 10^3$ L mol^{-1} s^{-1}, proceeds by hydride ion transfer. The Cr^{2+} so produced could be trapped as $CrOO^{2+}$ when O_2 was present, thereupon terminating the chain. $AcrH_2$ itself reacts with $Cr_2O_7^{2-} + H^+$, $k = 5.6 \times 10^3$ L^2 mol^{-2} s^{-1}, but this step is not an initiating reaction. Two successive electron-transfer steps are believed to occur between $Cr_2O_7^{2-}$ and $AcrH_2$, yielding $Cr^{IV} + Cr^{VI} + AcrH^+$.

Introduction

This research addresses the kinetics and mechanism of the reaction between 10-methyl-9,10-dihydroacridine ($AcrH_2$, Chart 1) and hydrogen chromate ions. The anaerobic reaction occurs rapidly, requiring techniques for fast reactions. In contrast, O_2 is a strong inhibitor, slowing the reaction by some 2 orders of magnitude. (This effect is clearly different, however, from the oxygen effect reported for ferricyanide oxidations.[1]) Together, these effects signal a chain mechanism in which O_2 acts in a chain-breaking capacity. A combination of conventional and stopped-flow UV methods has permitted the identification of two important intermediates, Cr(IV) and Cr(V). The recognition of these species and a delineation of their reactions and reactivity constitute the major part of this study.

Various mechanisms—one electron, hydride, or hydrogen atom transfer—have been proposed for reactions of dihydronicotinamide adenine dinucleotide (NADH) and its analogues.[2] These are the mechanisms known for NADH and its analogues in biological and artificial redox reactions.[3] The operative mechanisms have been explored in the $AcrH_2-HCrO_4^-$ system, for the reactions of Cr(V) and Cr(IV) as well as those of $HCrO_4^-$ itself.

Chart 1. Stable and Transient Species Derived from 10-Methyl-9,10-dihydroacridine



We did not use NADH, which is unstable toward acid-catalyzed hydrolysis,[4] but $AcrH_2$.[5] This acid-stable substance has been used to study biologically related reactions that utilize one-electron mechanisms via transient intermediates.[6,7] In addition to defining the role played by the transients $AcrH_2^{\bullet+}$ and $AcrH^\bullet$ (Chart 1), we sought to probe the Cr(V) and Cr(IV) species that are important intermediates in chromate reactions[8] and which are believed to contribute to the carcinogenic properties of chromium.[9] The reactivity of the Cr(IV) species

---

(1) Powell, M. F.; Wu, J. G.; Bruice, T. C. *J. Am. Chem. Soc.* **1984**, *106*, 3850.

(2) Eisner, U.; Kuthan, J. *Chem. Rev.* **1972**, *72*, 2. (b) Stout, D. M.; Mayer, A. I. *Chem. Rev.* **1982**, *82*, 223. (c) Shinkai, S.; Bruice, T. *Biochemistry* **1973**, *12*, 1750. (d) Kurz, L.; Frieden, C. *J. Am. Chem. Soc.* **1975**, *97*, 667l (e) Jones, J.; Taylor, K. *Can. J. Chem.* **1976**, *1976*, 54.

(3) Ohnishi, Y.; Ohno, A. *Catal. Lett.* **1976**, 697. (b) Kill, R.; Widdowson, D. *J. Chem. Soc., Chem. Commun.* **1976**, 697. (c) van Eikeren, P.; Grier, D. *J. Am. Chem. Soc.* **1977**, *99*, 8057. (d) Hajdu, J.; Sigman, D. *J. Am. Chem. Soc.* **1976**, *98*, 6060. (e) Schmakel, C.; Santhanathan, K.; Elving, P. *J. Electrochem. Soc.* **1974**, *121*, 345.

(4) van Eikeren, P.; Grier, D. L.; Eliason, J. *J. Am. Chem. Soc.* **1979**, *101*, 7406. (b) Kim, C. S. Y.; Cahykin, S. *Biochemistry* **1968**, *7*, 2339. (c) Fukuzumi, S.; Ishikawa, M.; Tanaka, T. *Tetrahedron* **1986**, *42*, 1021.

(5) (a) Fukuzumi, S.; Mariano, P. S., Ed.; JAI Press: Greenwich, CT, 1992; Vol. 2, p 65. (b) van Eikeren, P.; Grier, D. L. *J. Am. Chem. Soc.* **1976**, *98*, 4655. (c) Fukuzumi, S.; Kuroda, S.; Goto, T.; Ishikawa, K.; Tanaka, T. *J. Chem. Soc., Perkin Trans. 2* **1989**, 1047. (d) Fukuzumi, S.; Ishikawa, M.; Tanaka, T. *J. Chem. Soc., Perkin Trans.* **1989**, 1037. (e) Ishikawa, K.; Fukuzumi, S.; Goto, T.; Tanaka, T. *J. Am. Chem. Soc.* **1990**, *2*, 1577. (f) Fukuzumi, S.; Chiba, M.; Tanaka, T. *Chem. Lett.* **1989**, 31. (g) Fukuzumi, S.; Mochizuki, S.; Tanaka, T. *J. Am. Chem. Soc.* **1989**, *111*, 1497. (h) Fukuzumi, S.; Mochizuki, S.; Tanaka, T. *Inorg. Chem.* **1990**, *29*, 653. (i) Fukuzumi, S.; Tokuda, Y. *J. Phys. Chem.* **1993**, *97*, 3737.

(6) Fukuzumi, S.; Tokuda, Y.; Kitano, T.; Okamoto, T.; Otera, J. *J. Am. Chem. Soc.* **1993**, *115*, 8960.

10.1021/ja9823464 CCC: $15.00

$(H_2O)_5CrO^{2+}$ has been carefully defined.[10-12] Studies of the reactivity of Cr(V), on the other hand, have been more limited; the cationic transient *trans*-$(H_2O)LCrO^{3+}$ ion (L = [14]aneN$_4$) tends to undergo one-electron (1e) reactions,[13] as do other cationic Cr(V) complexes.[14-21]

Experimental Section

Materials. Most reagents were obtained from commercial sources. $AcrH_2$ and its 9,9′-dideuterated analogue $AcrD_2$ were prepared from 10-methylacridone and $LiAlH_4$ or $LiAlD_4$.[22] These compounds were stored and handled with minimal exposure to air. 10-Methylacridinium iodide ($AcrH^+$, Chart 1) was prepared from acridine and methyl iodide. Solutions of $Cr(H_2O)_6^{2+}$ were prepared by the zinc-amalgam reduction of hydrated chromium(III) perchlorate in 0.1 M perchloric acid. Solutions of CrO^{2+} were prepared in situ at pH 1.00 by the stopped-flow mixing of Cr_{aq}^{2+} (0.2−0.4 mM) and an air-saturated solution of O_2 in the presence of the desired substrate.[10]

Kinetics and Techniques. The kinetics studies were carried out 25.0 ± 0.2 °C in water−acetonitrile (4:1 by vol.), to provide for the solubility of the reaction components. The ionic strength, adjusted with perchloric acid and lithium perchlorate, was maintained at 1.00 M. A Shimadzu UV-3101 PC spectrophotometer was used for spectra and conventional kinetics. An Applied Photophysics instrument was used for anaerobic stopped-flow (SF) studies.

The concentrations of $AcrH_2$ were determined spectrophotometrically, $\epsilon_{285} = 1.32 \times 10^4$ L mol^{-1} cm^{-1}. The superoxochromium ion, $CrOO^{2+}$, was identified and determined at its absorption maximum, $\epsilon_{290} = 3.0 \times 10^3$ L mol^{-1} cm^{-1}.[23] The NMR and EPR data were obtained with Bruker 400 and Bruker ER 200 D-SRC instruments, respectively.

Results

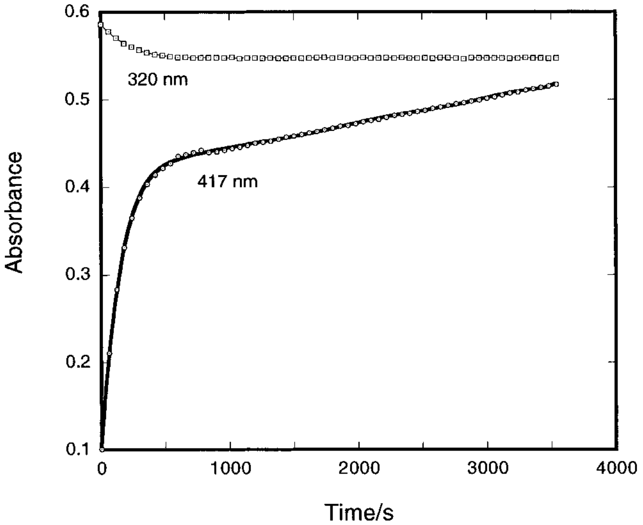


Figure 1. Kinetic trace monitoring the buildup of $AcrH^+$ at 417 nm for the reaction of $AcrH_2$ (200 μM) and hydrogen chromate ions (50 μM) at pH 1.0 and $\mu = 1.00$ M and 298 K. The slower, linear part of the trace was shown to be due to the reaction between $AcrH_2$ and dissolved oxygen. The kinetic trace for the same system is also shown at 320 nm, an isosbestic for $AcrH^+$ and $AcrH_2$, to monitor the loss of hydrogen chromate ions, which is complete within the faster portion of the reaction trace.

Reaction Stoichiometry. One set of determinations of the stoichiometry was made under air-free conditions with limiting $HCrO_4^-$ (20 μM). The anaerobic reaction occurred during mixing. The concentration of the $AcrH^+$ produced was determined spectrophotometrically at 358 and 417 nm. The stoichiometry is 1.44:1 and 1.47:1, from which this net reaction can be deduced:

$$3AcrH_2 + 2HCrO_4^- + 11H^+ = 3AcrH^+ + 2Cr_{aq}^{3+} + 8H_2O \quad (1)$$

When oxygen-saturated solutions were used under the same experimental conditions, $AcrH^+$ was formed more slowly, over ~20 min. The reaction was monitored by the buildup of $AcrH^+$ at 417 nm. At an initial ratio $AcrH_2$:$HCrO_4^-$ of 10:1, the reaction occurred in two stages, as depicted in Figure 1. The same experiment was then monitored at 320 nm, where $AcrH_2$ and $AcrH^+$ have an isosbestic point ($\epsilon_{320} = 2.75 \times 10^3$ L mol^{-1} cm^{-1}). The consumption of $HCrO_4^-$ ($\epsilon_{320} = 7.7 \times 10^2$ L mol^{-1} cm^{-1}) was complete during the time needed for the first stage at 417 nm, Figure 1. Thus, the slowly trailing absorbance at 417 nm can be attributed to the oxidation of $AcrH_2$ with oxygen. To assess the stoichiometry, the kinetic profile at 417 nm was fit to a linear + exponential function, the amplitude of which gave the concentration of $AcrH^+$ produced by chromate oxidation. In this way the stoichiometry in oxygen-saturated solution was (1.88 ± 0.06):1, which we interpret as 2:1. The stoichiometry is consistent with either of these net equations, depending on the form of the chromium(III) product:

$$4AcrH_2 + 2HCrO_4^- + {}^1/_2O_2 + 12H^+ = 4AcrH^+ + 2Cr_{aq}^{3+} + 9H_2O \quad (2a)$$

$$2AcrH_2 + HCrO_4^- + O_2 + 5H^+ = 2AcrH^+ + CrOO^{2+} + 4H_2O \quad (2b)$$

A further series of experiments was performed to investigate the effect of methanol, a trap for the CrO^{2+} ion that may be an intermediate under air-free conditions. The yield of $AcrH^+$ declined systematically with increasing [MeOH], being 100% without MeOH (relative to the expectation from eq 1), 68%

---

(7) (a) *Free Radicals in Biology*; Kosower, E. M., Pryor, W. A., Eds.; Academic Press: New York, 1976; Vol. II, p 1. (b) Kill, R. J.; Widdowson, D. A. In *Bioorganic Chemistry*; van Tamelen, E. E., Ed.; Academic Press: New York, 1978; Vol. IV, p 239. (c) Bruice, T. C. In *Progress in Bioinorganic Chemistry*; Kaiser, F. T., Kezdy, F. J., Eds.; Wiley: New York, 1976; Vol. IV, p 1. (d) Yasui, S.; Ohno, A. *Bioorg. Chem.* **1986**, *14*, 70.

(8) Cainelli, G.; Cardillo, G. *Chromium Oxidations in Organic Chemistry*; Springer-Verlag: New York, 1984.

(9) (a) Rossi, S. C.; Gorman, N.; Wetterhahn, K. E. *Chem. Res. Toxicol.* **1988**, *1*, 101. (b) Goodgame, D. M. L.; Joy, A. M. *J. Inorg. Biochem.* **1986**, *26*, 219. (c) Farrell, R. P.; Judd, R. J.; Lay, P. A.; Dixon, N. E.; Baker, R. S. U.; Bonin, A. M. *Chem. Res. Toxicol.* **1989**, *2*, 227−229.

(10) Scott, S. L.; Bakac, A.; Espenson, J. H. *J. Am. Chem. Soc.* **1992**, *114*, 4205−4213.

(11) Al-Ajlouni, A. M.; Espenson, J. H.; Bakac, A. *Inorg. Chem.* **1993**, *32*, 3162.

(12) Al-Ajlouni, A.; Bakac, A.; Espenson, J. H. *Inorg. Chem.* **1993**, *32*, 5792.

(13) Bakac, A.; Wang, W.-D. *J. Am. Chem. Soc.* **1996**, *118*, 10325.

(14) Krumpolc, M.; Rocek, J. *J. Am. Chem. Soc.* **1979**, *118*, 3206.

(15) Srinivasan, K.; Kochi, J. K. *Inorg. Chem.* **1985**, *24*, 4670.

(16) Ghosh, M. C.; Gould, E. S. *J. Am. Chem. Soc.* **1993**, *115*, 3167.

(17) Sugden, K. D.; Wetterhahn, K. E. *Inorg. Chem.* **1996**, *35*, 651.

(18) Siddall, T. L.; Miyaura, N.; Huffman, J. C.; Kochi, J. K. *J. Chem. Soc., Chem. Commun.* **1983**, 1185.

(19) Yuan, L.-C.; Bruice, T. C. *J. Am. Chem. Soc.* **1985**, *107*, 512.

(20) Mitewa, M.; Russev, P.; Bontchev, P. R.; Kabassanov, K.; Mallinovski, A. *Inorg. Chim. Acta* **1983**, *70*, 179.

(21) Bakac, A. *Prog. Inorg. Chem.* **1995**, *43*, 267−351.

(22) Karrer, P.; Szabo, L.; Krishna, H. Y. V. *Helv. Chim. Acta* **1950**, *XXXIII*, 294.

(23) (a) Ilan, Y. A.; Czapski, G.; Ardon, M. *Isr. J. Chem.* **1975**, *13*, 15−21. (b) Sellers, R. M.; Simic, M. *J. Am. Chem. Soc.* **1976**, *98*, 6145.

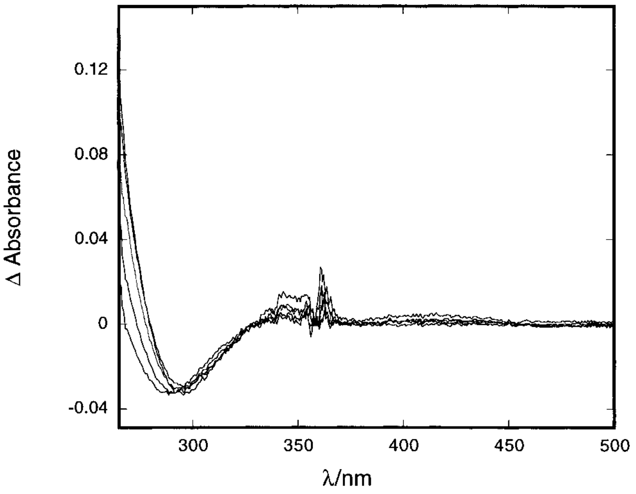


Figure 2. Difference spectrum from the reaction of $AcrH_2$ (80 μM) with hydrogen chromate ions (40 μM) and Fe_{aq}^{2+} (200 μM) at pH 1.00, μ 1.0 M, at 298 K. The Fe^{2+} was added after the other reactions were complete as a reagent for $CrOO^{2+}$. The spectral changes shown represent the absorbance differences before and immediately after the addition of Fe^{2+}.

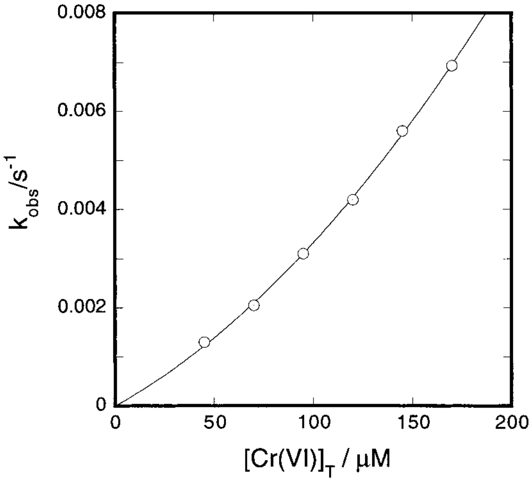
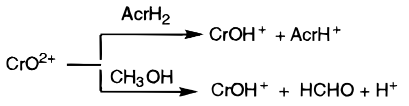


Figure 3. Pseudo-first-order rate constant for the reaction between $AcrH_2$ (20 μM) and hydrogen chromate ions (50−175 μM) in oxygen saturated solutions at pH 1.00, μ 1.00 M, and 298 K defines a parabolic function, signaling the contribution of dichromate ions, present only in much lower concentration than $HCrO_4^-$, to the overall reaction.

(0.83 M MeOH), and 57% (2.5 M MeOH). This result signals the competing reactions of methanol and $AcrH_2$ with CrO^{2+}, the chromium(IV) intermediate.[10]



(3a)
(3b)

Because the superoxochromium(2+) ion may (or may not, see eq 2) be formed, an attempt was made to detect it among the products. It is a metastable species that has not been isolated, even though it has been well-characterized in terms of spectroscopy and reactivity.[24] A solution was made up to contain 40 μM $HCrO_4^-$ and 80 μM $AcrH_2$ (the stoichiometric ratio) at 0.100 M H^+ in an O_2-saturated solution. After the reaction was finished, 200 μM Fe^{2+} was added to bring about this reaction:

$$CrOO^{2+} + 3Fe^{2+} + 4H^+ = Cr_{aq}^{3+} + 3Fe_{aq}^{3+} + 2H_2O \qquad (4)$$

The spectrum was recorded every 2 min. Each spectrum was subtracted from that prior to Fe^{2+} addition, after correction for the small dilution. The very slight excess of $AcrH_2$ required a correction (because $AcrH_2$ and Fe^{3+} yield $AcrH^+$ in two steps). Finally, the absorbance contributions of $AcrH^+$, $AcrH_2$, and Fe^{3+} were allowed for in this calculation. What remains is a difference spectrum between the final solution and that after the addition of Fe^{2+}. As shown in Figure 2, there is a negative absorbance difference around 290 nm, consistent with the presence of $CrOO^{2+}$ ($\epsilon_{290} = 3 \times 10^3$ L mol^{-1} cm^{-1}).[23]

Kinetics in Oxygen- and Air-Saturated Solutions. With an excess of chromate (20 μM $AcrH_2$, 0.2−1.75 mM $HCrO_4^-$), the kinetic data followed a pseudo-first-order rate law. Experiments were performed with varying $[HCrO_4^-]$ at $[H^+] = 0.100$ M and with varying $[H^+]$ (0.05−0.3 M) at fixed $[HCrO_4^-]$ (200 μM). The value of k_ψ was directly proportional to $[H^+]$; see Figure S1. The experiments at varying $[HCrO_4^-]$ had a parabolic shape consistent with the parallel reaction of $Cr_2O_7^{2-}$ (Figure 3), this effect arising from the dimerization equilibrium, $2HCrO_4^- = Cr_2O_7^{2-} + H_2O$, $K_d = 98$ L mol^{-1} at 298 K.[25] This value applies to aqueous solutions but is not likely to be different in the 80% aqueous medium used here. Given K_d, the concentrations of $HCrO_4^-$ and $Cr_2O_7^{2-}$ can be related to $[Cr^{VI}]_T$. Actually, at these low concentrations, only a minor proportion is dichromate (4% at the highest), so without great loss of accuracy, $[Cr^{VI}]_T$ can be replaced by $[HCrO_4^-]$ and, where desired, $[Cr_2O_7^{2-}]$ by $K_d[HCrO_4^-]^2$. The rate law under these conditions is given by

$$-\frac{d[AcrH_2]}{dt} = 2[H^+]\{k[HCrO_4^-] + k'[Cr_2O_7^{2-}]\}[AcrH_2]$$
$$= 2[H^+]\{k + K_d k'[HCrO_4^-]\} \times [HCrO_4^-][AcrH_2] \qquad (5)$$

where "2" is the stoichiometric factor relating the pair of reactants. Least-squares fitting gave these values for the respective third-order rate constants: $k = (1.12 \pm 0.04) \times 10^2$ L^2 mol^{-2} s^{-1} and $k' = (5.6 \pm 0.3) \times 10^3$ L^2 mol^{-2} s^{-1}. One cannot display the fit of the data on a two-dimensional graph, and so we have constructed a plot of observed vs calculated values of k_ψ, Figure S-2. It is apparent from the numerical parameters that the less abundant dichromate is considerably more reactive than the hydrogen chromate ion. This is a striking effect because in most systems the hydrogen chromate ion is much more reactive than dichromate. We return to this point in the Discussion.

Experiments with excess $AcrH_2$ (200 μM) over $HCrO_4^-$ (20 μM) required use of the linear + exponential function. The data were fitted to eq 6 by use of the program Kaleidagraph. The linear variation of k_ψ with $[H^+]$ (Figure S-3) confirms the first-order $[H^+]$ dependence. A variation of $AcrH_2$ was also undertaken, but the data were not fully reliable owing to interference of the $AcrH_2$−O_2 reaction and so are not presented.

$$Abs_t = (Abs_\infty - Abs_0)\{1 - e^{-k_\psi t}\} + mt + Abs_0 \qquad (6)$$

The reaction was also carried out by making three successive injections of $AcrH_2$ into excess $HCrO_4^-$. This procedure led to a uniform increase in $AcrH^+$. With reversed concentrations,

---

(24) (a) Brynildson, M. E.; Bakac, A.; Espenson, J. H. *Inorg. Chem.* **1988**, *27*, 2592. (b) Brynildson, M. E.; Espenson, J. H.; Bakac, A. *J. Am. Chem. Soc.* **1987**, *109*, 4579.

(25) Tong, J. Y.; King, E. L. *J. Am. Chem. Soc.* **1953**, *75*, 6180−6186.

however, the incremental buildup of $AcrH^+$ grew smaller in each successive stage (Figure S-4), again symptomatic of the loss of $AcrH_2$ to oxygen.

Kinetics under Air-Free Conditions. The SF technique was used to monitor the buildup of $AcrH^+$ at 358 or 417 nm. The rates were significantly higher, some 10−250-fold higher than those for experiments with oxygen present, with $HCrO_4^-$ or $AcrH_2$, respectively, taken in excess. With either reagent in >10-fold excess, pseudo-first-order kinetics was followed. Figures S-5 and S-6 show the linear dependencies of k_ψ on $[H^+]$ and $[AcrH_2]$ ($AcrH_2$ in excess). The fitting of these data to the third-order rate law gives $k_7 = (2.49 \pm 0.04) \times 10^4$ L^2 mol^{-2} s^{-1}.

$$-\frac{d[HCrO_4^-]}{dt} = k_7[AcrH_2][HCrO_4^-][H^+] \qquad (7)$$

With chromate in excess, the k_ψ values showed a linear dependence on $[HCrO_4^-]$ (Figure S-7). The seeming discrepancy between that rate law and eq 5, with the quadratic form, signals that only the pathway defined by the first term of eq 5 serves to initiate the chain reaction; this matter will be taken up in the Discussion. The variation of k_ψ with H^+ (0.05−0.70 M) led to the rate law in eq 8, with the parameters $k_8 = (1.10 \pm 0.03) \times 10^3$ L^2 mol^{-2} s^{-1} and $\kappa = 1.9 \pm 0.1$ L mol^{-1} (see Figure S-8).

$$v = \frac{k_8[AcrH_2][HCrO_4^-][H^+]}{1 + \kappa[H^+]} \qquad (8)$$

A series of experiments with SO_4^{2-} added to reactions with excess $AcrH_2$ were performed to assess the possibility of ion-pair formation of chromate ions. Sulfate to 0.05 M gave the same rate constants as in its absence, implying that ion pairing is negligible.

Kinetic Isotope Effects. The 9,9′-dideuterio analogue $AcrD_2$ was used in D_2O−CH_3CN solvent. In O_2-saturated solution, data were collected over a range of $[DCrO_4^-]$ (50−175 μM, the excess reagent) at 0.10 M D^+. The fit to eq 5 gave $k^D = (9.4 \pm 1.7) \times 10^1$ L^2 mol^{-2} s^{-1} and $k'^D = (6.5 \pm 1.2) \times 10^3$ L^2 mol^{-2} s^{-1}. Thus the kie's are as follows: k, 1.2 ± 0.2; k', 0.86 ± 0.17. The compensation effect makes each kie seem larger than it really is, and we take both to be within experimental error of unity. Under air-free conditions and with chromate still in excess, again no kie was found. When excess $AcrD_2$ was employed under argon, there was a mild kie $k^H/k^D = 1.71 \pm 0.06$.

The kie for the composite rate constant for the chain reaction, consisting of a step between Cr(VI) and $AcrH_2$, was obtained from $AcrD^+/AcrH^+$ product ratios in NMR experiments in which a precise mixture of $AcrH_2$ (40−100 μM) and $AcrD_2$ (100−200 μM) was allowed to react with a deficiency of chromate (20 μM). After the reaction was complete, the ^{1}H spectrum was acquired in very long scans. The ratio $R = [AcrH^+]_\infty/[AcrD^+]_\infty$ was determined from the relative peak areas for the proton in position 9 (I_a) compared to those in positions 1−8 (I_b). The equations are $R = 8I_a/(I_b - 8I_a)$; $[AcrH^+]_\infty = R\Delta/(R + 1)$; $[AcrD^+]_\infty = \Delta/(R + 1)$, where $\Delta = {}^3/_2[Cr^{VI}]_0$, because the stoichiometry in eq 1 applies. The kie for the chain reaction was then obtained from

$$\left(\frac{k^H}{k^D}\right)_{chain} = \frac{\ln\left\{\dfrac{[AcrH_2]_0}{[AcrH_2]_0 - [AcrH^+]_\infty}\right\}}{\ln\left\{\dfrac{[AcrD_2]_0}{[AcrD_2]_0 - [AcrD^+]_\infty}\right\}} \qquad (9)$$

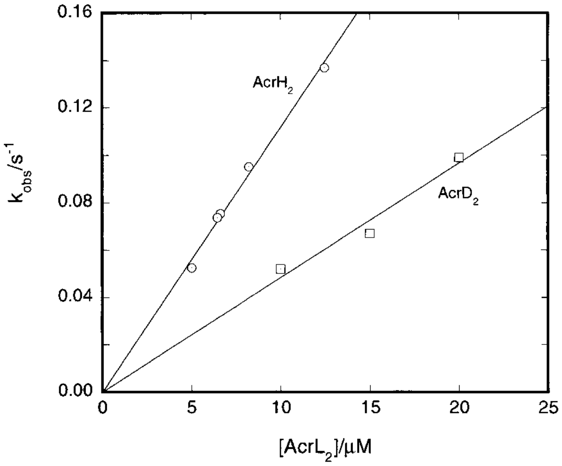


Figure 4. Kinetic data for the reactions of CrO^{2+} (~1.5 μM) with $AcrH_2$ (5−12.5 μM) and $AcrD_2$ (10−20 μM) at pH 1 and μ 1.0 M in air-saturated solutions.

Owing to the resolution of the NMR instrumentation and some interference from HOD, because traces of nondeuterated water were present in the $DClO_4$ stock solution, the result has a sizable error: $(k^H/k^D)_{chain} = 3.0 \pm 1.1$. Isotope incorporation from the solvent to the products was found to be unimportant in the control reactions, oxidation of $AcrH_2$ in D_2O and oxidation of $AcrD_2$ in H_2O.

The Reaction of Chromyl Ion with $AcrH_2$. An anaerobic solution of Cr_{aq}^{2+} (300 μM) was mixed with an equal volume of an air-saturated solution of $AcrH_2$ (100−200 μM) using an SF apparatus.[10] The concentration of CrO^{2+} so generated was determined from the absorbance of $AcrH^+$ at 358 nm; in repeat experiments, 60 ± 10 μM CrO^{2+} was obtained. This procedure was repeated, but with $AcrH_2$ in the same arm of the SF instrument as Cr^{2+}, to study the reaction between $AcrH_2$ and CrO^{2+} (reaction C), $k = (1.02 \pm 0.08) \times 10^4$ L mol^{-1} s^{-1}.

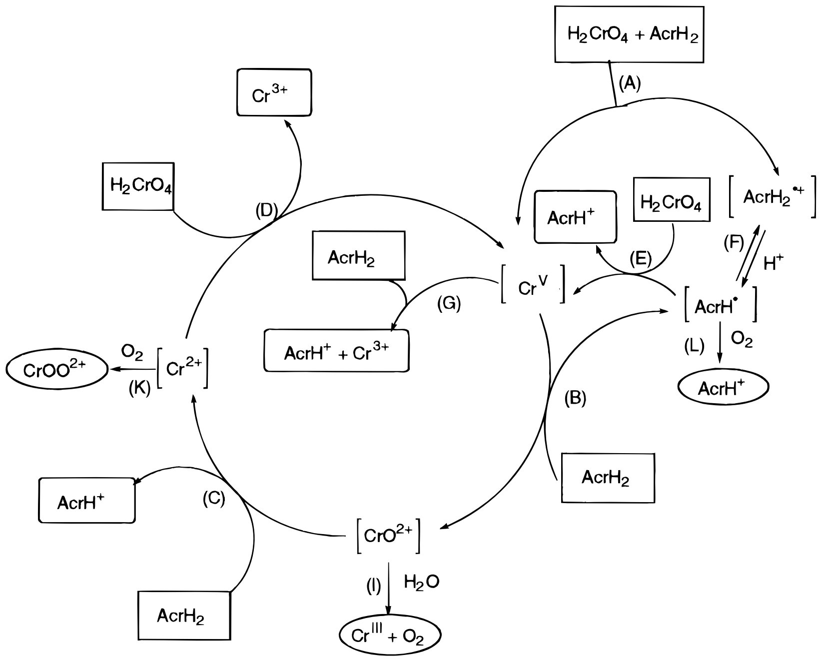
To confirm this rate constant, CH_3OH was used as the competing reagent, as in eq 3. While trying to maintain the conditions identical, despite the transient nature of CrO^{2+}, the reaction was conducted with 0.1 M CH_3OH only ($k_\psi = 4.68$ s^{-1}, as expected[10]) and with 200 μM $AcrH_2$ as well. The experimental rate constant was $k = 6.43$ s^{-1}. The expected value of k, using the rate constant cited in the preceding paragraph is 4.68 + 2.04 = 6.72 s^{-1}. The agreement between the two is within 5%.

In a separate experiment CrO^{2+} was prepared as described, then diluted to a concentration of 1.5 μM. It was then allowed to react with $AcrH_2$ (5.0−12.5 μM) in a conventional UV/vis instrument. The rate constant was $(1.10 \pm 0.06) \times 10^4$ L mol^{-1} s^{-1}, which agrees well with the value from the SF experiments. For $AcrD_2$ under the same conditions, $k = (4.8 \pm 0.2) \times 10^3$ L mol^{-1} s^{-1} (Figure 4). Thus the kie is $k_H/k_D = 2.29 \pm 0.16$.

Interpretation and Discussion

A chain mechanism is implicated by the change in stoichiometry with oxygen present and by the marked rate-inhibiting effect of oxygen. Other facts bearing directly on the mechanism are the chromium products with and without oxygen and the absence of a kie for the overall reaction under oxygen. The formation of $CrOO^{2+}$ established that Cr^{2+} is an intermediate, and it further demonstrates that, not surprisingly, $CrOO^{2+}$ does not react with $AcrH_2$. The only product from $AcrH_2$ is $AcrH^+$, representing a net two-electron (2e) oxidation. The stoichiometry

Scheme 1. Major Reactions for the Chain Mechanism Showing Starting Materials (Rectangles), Intermediates (Brackets), Products (Rounded Corners), and Products in the Presence of Oxygen (Ovals)[a]



[a] The letters in parentheses are the reaction designations from Table 1.

Table 1. Chemical Reactions Involved in the Chain Oxidation of Dihydroacridine by Chromium(VI)

rxn	chemical equation	role[a]	rate constant[b]
	Part I. The Major Reactions		
A	$AcrH_2 + H_2CrO_4 \rightarrow AcrH_2^{\bullet +} + H_2CrO_4^-$	I	4.6×10^{2c}
B	$AcrH_2 + Cr^V \rightarrow AcrH^\bullet + Cr^{IV}$	P (B)	$[\sim 1 \times 10^8]^{c,d}$
C	$AcrH_2 + Cr^{IV} \rightarrow AcrH^+ + Cr^{II}$	P	1.0×10^{4c}
D	$Cr^{VI} + Cr^{II} \rightarrow Cr^V + Cr^{III}$	P	2×10^{9e}
E	$Cr^{VI} + AcrH^\bullet \rightarrow Cr^V + AcrH^+$	P	$(7.4 \times 10^9)^f$
F	$AcrH_2^{\bullet +} \rightleftarrows AcrH^\bullet + H^+$		$690\ s^{-1}$, 1.2×10^{5g}
G	$AcrH_2 + Cr^V \rightarrow AcrH^+ + Cr^{III}$	T	$[\sim 2 \times 10^7]^{c,d}$
H	$AcrH^\bullet + Cr^{IV} \rightarrow AcrH^+ + Cr^{III}$	T	$(7.4 \times 10^9)^f$
I	$Cr^{IV} \rightarrow Cr^{III}$	T	$0.1\ s^{-1h}$
J	$Cr^{II} + Cr^{IV} \rightarrow 2Cr^{III}$	T	$\sim 1 \times 10^9$
	Part II. Reactions Important under Oxygen		
K	$Cr^{II} + O_2 \rightarrow CrOO^{2+}$	$X-O_2$	1.6×10^{8i}
L	$AcrH^\bullet + O_2 \rightarrow Acr(H)OO^\bullet$	$X-O_2$	4.3×10^{9j}
	Part III. Reactions of Negligible Importance under Chain Reaction Conditions		
M	$Cr^{II} + Cr^V \rightarrow Cr^{III} + Cr^{IV}$	T	
N	$AcrH^\bullet + Cr^V \rightarrow AcrH^+ + Cr^{IV}$	T	$(7.4 \times 10^9)^f$
O	$AcrH^\bullet + AcrH_2^{\bullet +} \rightarrow AcrH^+ + AcrH_2$	T	$(7.4 \times 10^9)^f$
P	$2\ Cr^V \rightarrow Cr^{IV} + Cr^{VI}$	T	
Q	$AcrH_2 + Cr_2O_7^{2-} + H^+ \rightarrow AcrH^+ + CrO^{2+} + HCrO_4^-$		$(5.6 \pm 0.3) \times 10^3\ L^2\ mol^{-2}\ s^{-1\,k}$

[a] Designated as initiation (I), propagation (P), branching reaction (B), termination (T), or termination under oxygen ($X-O_2$). [b] Rate constants at 298 K and 0.10 M H^+ in units of L mol^{-1} s^{-1} except as noted. The diffusion-controlled rate constant is 7.4×10^9 L mol^{-1} s^{-1}. [c] This work. [d] Individual values are estimates only, but the ratio k_B/k_G was determined experimentally. [e] Reference 10. [f] Diffusion-controlled rate assumed. [g] Reference 28. [h] In water, $k \sim 0.02\ s^{-1}$, ref 10. [i] Reference 23. [j] Estimated from the effect of O_2 on the stoichiometry of the $IrCl_6^{2-}$ reaction, ref 28. [k] Since the pK_a of $HCr_2O_7^-$ is not known, the bimolecular rate constant cannot be obtained.

shows that the final chromium product under anaerobic conditions must be chromium(III). To aid in the discussion of the complex pattern of reactions, we first present the contributing reactions in Scheme 1. Many of these and other reactions and their rate constants are summarized in Table 1.

The experiments with methanol provided kinetic evidence for CrO^{2+}, by virtue of its partitioning between $AcrH_2$ and methanol (eq 3). The reduction of CrO^{2+} by $AcrH_2$ (as well as by MeOH) yields Cr_{aq}^{2+}, which transforms oxygen into $CrOO^{2+}$, the superoxochromium(III) ion.[9d,e,24] This species was confirmed by its characteristic absorption at 290 nm, which disappeared when Fe^{2+} was added to convert $CrOO^{2+}$ to Cr_{aq}^{3+}. It should also be noted that, with oxygen present, the stoichiometry of reaction 2 requires a formal Cr(II) species be generated. Taken together, these data allow us to assign a 2e process, probably hydride abstraction, to this reaction:

$$AcrH_2 + CrO^{2+} + H^+ \rightarrow AcrH^+ + Cr^{2+} + H_2O \quad (10)$$

Further support for this mechanism comes from the kie, $k^H/k^D = 2.3$. This mechanism could not have been predicted reliably at the outset, however, because the alternative products, $AcrH_2^{\bullet +} + Cr^{3+}$, are not unreasonable and $\Delta G°$ is -108 kJ mol^{-1} for the alternative vs -65 kJ mol^{-1} for reaction 10. On the other hand, the hydride pathway is fully acceptable in that most reactions of CrO^{2+} with other reagents, including every alcohol examined except cyclobutanol, are known to adopt the hydride pathway.[10] A 1e process with CrO^{2+} will occur, of course, with 1e donors, such as Fe^{2+} in the example chosen here.

The Initiating Step. Oxygen greatly reduces the reaction rate, breaking the chain cycle. The rate constants under oxygen therefore provide a measure of the rate of initiation. The reaction between $AcrH_2$ and H_2CrO_4 can be inferred to proceed by a 1e mechanism because $AcrH_2$ and $AcrD_2$ react at the same rate. We note that the order of the reaction with respect to $[H^+]$ is unity, that $AcrH_2$ has no site of protonation, and that H_2CrO_4 is a reasonably strong acid with $K_a = 4.16$.[26] Despite H_2CrO_4 being a minor species relative to $HCrO_4^-$, the initial reaction involves it as one reactant:

$$AcrH_2 + H_2CrO_4 \rightarrow AcrH_2^{\bullet +} + H_2CrO_4^- \qquad (11)$$

where $H_2CrO_4^-$ is the chromium(V) species required to balance the equation with the known species involved in the reaction. From the third-order rate constant from eq 5 and K_a (H_2CrO_4), we obtain $k_{11} = (4.36 \pm 0.18) \times 10^2$ L mol^{-1} s^{-1}. The second (k') term in eq 5, that involving $HCr_2O_7^-$, has a rate law $v = k'[AcrH_2][Cr_2O_7^{2-}][H^+]$, with $k' = (5.6 \pm 0.3) \times 10^3$ L^2 mol^{-2} s^{-1}.[27]

The dichromate pathway, however, does not contribute to chain initiation. We propose that the reaction between $AcrH_2$ and $HCr_2O_7^-$ occurs by two 1e steps in such rapid succession that the intermediate mixed-valent (Cr^V-Cr^{VI}) species cannot dissociate. The transfer of the second electron and the required deprotonation of intermediate $AcrH_2^{\bullet +}$ probably occur within a solvent cage. This proposal, which presents a reaction that cannot sustain the chain, is represented by eq 12. That the caged intermediate should give the products shown and not $2Cr^V$ is consistent with Cr(V) being a much more powerful 1e oxidant than Cr(VI).

$$HCr_2O_7^- + AcrH_2 \rightarrow \{HCr_2O_7^{2-}, AcrH_2^{\bullet +}\} \xrightarrow{H^+} CrO^{2+} + HCrO_4^- + AcrH^+ \qquad (12)$$

It seems unlikely that $AcrH_2^{\bullet +}$ is itself an intermediate in the scheme because it cannot be further oxidized by simple electron transfer. $AcrH_2^{\bullet +}$ is short-lived with respect to the acid-ionization step in eq F, for which $k_i^H = 6.9 \times 10^2$ L mol^{-1} s^{-1} and $k_i^D = 1.06 \times 10^2$ L mol^{-1} s^{-1}.[28] The ionization of $AcrH_2^{\bullet +}$ gives rise to the most important chain-carrying organic intermediate, $AcrH^\bullet$. This species sustains the chain by a 1e reaction with chromium(VI), $HCrO_4^-$ or H_2CrO_4, to generate chromium(V) (reaction E). Many reactions of $AcrH^\bullet$ with 1e acceptors (e.g., Fe_{aq}^{3+}, $IrCl_6^{2-}$) occur at the diffusion-controlled rate, and it is plausible to suggest the same for H_2CrO_4. The implied rapidity of reaction E means in addition that the self-reaction of $AcrH^\bullet$ is not important in this scheme. This is reasonable because radical−radical reactions (such as those in eq M−Q) are inherently disfavored by their concentrations, even if diffusion-controlled.

The Propagation Steps. The rate of oxidation of $AcrH_2$ by CrO^{2+} (reaction C) was directly measured. As noted earlier,[10] CrO^{2+} is not highly reactive despite its high $E°$ values for 1e and 2e reactions, Cr(IV)/Cr(III) ($E° \sim 1.8$ V) and Cr(IV)/Cr(II) ($E° \sim 0.7$ V). Reaction C is clearly a 2e reaction, proceeding most likely by a hydride-ion abstraction, given the kie and the evidence for Cr(II). The rate constant for $Cr^{2+} + HCrO_4^-$ (reaction D), another chain propagating reaction, has been determined independently.[10]

The most interesting of the propagation steps occurs between $AcrH_2$ and Cr(V) (reaction B), a branching reaction that produces two chain carriers from one. Its inclusion is necessary for an effective chain mechanism. A kie of 1.71 for the overall chain reaction cannot be attributed to the initiation step because its kie is ∼1. The two product forming reactions [steps C and E (kinetics controlled by step B)] have respective kie's designated kie_C and kie_B. They can be used to derive an expression for the kie of the overall chain, $(k^H/k^D)_{chain}$,which was directly evaluated as explained earlier. The relations are

$$\left(\frac{k^H}{k^D}\right)_{chain} = \frac{2kie_B \times kie_C + kie_B + kie_C}{2 + kie_B + kie_C} \qquad (13)$$

From that, kie_B can be obtained:

$$kie_E = \frac{\left(\frac{k^H}{k^D}\right)_{chain} \times kie_C + 2\left(\frac{k^H}{k^D}\right)_{chain} - kie_C}{2kie_C + 1 - \left(\frac{k^H}{k^D}\right)_{chain}} \qquad (14)$$

Since the quantities on the right-hand side of eq 14 were determined directly, we find $kie_E = 4.1 \pm 3.2$. The algebraic form tends to amplify the errors, but the result, despite the low precision, is consistent with hydrogen-atom abstraction as the mechanism for the single electron reaction between $AcrH_2$ and Cr(V).

The Termination Step. The kinetic modeling showed that the only significant termination reaction was the hydride abstraction from $AcrH_2$ (reaction G). The other reactions that are possible termination steps were considered (Table 1, Part II) but all proved negligible according to the kinetic analysis. It was, however, necessary to postulate the concurrent unimolecular loss of Cr(IV) (reaction I) for which there is some precedent.[10,11]

Change in the Excess Reagent. To reiterate, the rate constant for the chain reaction under anaerobic conditions was $k_7 = 2.49 \times 10^4$ L^2 mol^{-2} s^{-1} with $AcrH_2$ in excess but $k_8 = 9.2 \times 10^2$ L^2 mol^{-2} s^{-1} (interpolated to 0.1 M H^+) with $HCrO_4^-$ in excess. There is a factor of 25 between the two determinations of supposedly the same quantity. Experiments with added SO_4^{2-} eliminated ion-pairing effects as being responsible for the lower rate with excess chromate. Kinetic modeling of this complicated scheme suggested that the "second cycle" in Scheme 1 (that is, steps C and D) is not contributing appreciably when $HCrO_4^-$ is in excess. The competing decomposition of chromyl ions (step I) thus becomes much faster than the second propagating reaction C. As a result, reactions C and D become unimportant. Further support comes from the experiments with MeOH added at the start, designed to promote the formation of Cr^{2+} from CrO^{2+} without formation of $AcrH^+$. These reactions were much faster than without methanol, resembling the chain reactions with excess $AcrH_2$.

---

(26) Tong, J. Y. *Inorg. Chem.* **1964**, *3*, 1804−1805.

(27) Because the pK_a of $HCr_2O_7^-$ is not known, the bimolecular rate constant cannot be obtained from the value of k′.

(28) Pestovsky, O.; Bakac, A.; Espenson, J. H. *Inorg. Chem.* **1998**, *37*, 1616−1622.

A steady-state rate law can be derived for the limited scheme (that is, with omission of steps C and D):

$$-\frac{d[AcrH_2]}{dt} = \frac{2k_A k_B}{k_G}[AcrH_2][H_2CrO_4] \qquad (15)$$

The estimated chain length is k_B/k_G, or 4.3. This indicates a rather inefficient chain, consistent with only an ∼10-fold retardation in the presence of oxygen.

Acid Effects. The saturation effect in $[H^+]$ seen in eq 8 is unusual, since it is characteristic only of the chain reaction and not of the initiation step. To consider this, one must take into account the speciation of Cr(V) as $f([H^+])$. pK_a values have been reported for H_3CrO_4 (pK_{a1} 2.7), $H_2CrO_4^-$ (pK_{a2} 3.0), and $HCrO_4^-$ (pK_{a3} 7).[29] No reference to $H_4CrO_4^+$ was made in that study, but to account for our findings, we postulate its existence as a reasonably or very strong acid. Further, we take it to be a more reactive 2e oxidizing agent than H_3CrO_4, since its positive charge should facilitate hydride abstraction, as in eq G. The overall rate of the chain reaction can be expressed as

$$v = \left(\frac{2k_A k_B k_{a0}}{k_{G_a}}\right)\left(\frac{[H^+]}{\frac{k_{G_b}K_{a0}}{k_{G_a}} + [H^+]}\right)[AcrH_2][HCrO_4^-] \qquad (16)$$

where K_{a0} is the K_a of $H_4CrO_4^+$ and k_{Ga} and k_{Gb} are the respective rate constants for the reactions of $AcrH_2$ with $H_4CrO_4^+$ and H_3CrO_4. In this derivation two reasonable assumptions were made: $[H_3CrO_4] \cong [Cr^V]_T$ over the pH range and $[H_4CrO_4^+] \cong [Cr^V]_T \times [H^+]/K_{a0}$. From the experimental data, $k_B/k_{Gb} = 4.9$ and $k_{Gb}K_{a0}/k_{Ga} = 0.54$. Thus the reaction of $AcrH_2$ with H_3CrO_4 prefers H-atom abstraction over hydride abstraction by a ratio of 4.9:1.

Conclusions. The oxidation of $AcrH_2$ by acidic chromate is a branching chain reaction in which transient species of Cr^V, CrO^{2+}, Cr^{2+}, and $AcrH^\bullet$ are chain carriers. $AcrH_2^{\bullet+}$ also intervenes, but not as a chain carrier. Two interconnected chain pathways operate concurrently, and both are broken by molecular oxygen. The initiation step is electron transfer between $AcrH_2$ and H_2CrO_4. A second pathway for that step, the reaction of $HCr_2O_7^-$, occurs but does not initiate the chain reaction.

Appendix

Derivation of Expressions 13 and 14. At $[AcrH_2]_0 = [AcrD_2]_0$, the product ratio $[AcrH^+]/[AcrD^+]$ = kie. Thus

$$([AcrH^+]/[AcrD^+])_B = \mathrm{kie}_B$$

$$([AcrH^+]/[AcrD^+])_C = \mathrm{kie}_C$$

Under a long chain approximation, $\mathrm{rate}_B = \mathrm{rate}_C$, i.e.,

$$[AcrH^+]_B + [AcrD^+]_B = [AcrH^+]_C + [AcrD^+]_C = 0.5c_0$$

where c_0 represents the total concentration of the product.

From the above equations one obtains

$$[AcrD^+]_B = 0.5\ c_0/(1+ \mathrm{kie}_B)$$

$$[AcrH^+]_B = 0.5\ c_0\ \mathrm{kie}_B/(1 + \mathrm{kie}_B)$$

$$[AcrD^+]_C = 0.5\ c_0/(1 + \mathrm{kie}_C)$$

$$[AcrH^+]_C = 0.5\ c_0\ \mathrm{kie}_C/(1 + \mathrm{kie}_C)$$

Upon substitution of these terms into the experssion

$$(k_H/k_D)_{chain} = ([AcrH^+]_B + [AcrH^+]_C)/([AcrD^+]_B + [AcrD^+]_C)$$

one obtains eq 13, which upon rearrangement gives the expression for kie_B in eq 14.

Acknowledgment. This research was supported by a grant from the National Science Foundation (CHE-9007283). We thank Dr. Matthew D. Eager for valuable discussions about the chain mechanism and a reviewer for presenting an alternative view of Scheme 1 (shown in the Supporting Information). Some experiments were conducted with the use of the facilities of the Ames Laboratory.

Supporting Information Available: Plots of kinetic data to illustrate agreement to selected mathematical forms and to evaluate numerical parameters, and an alternative presentation of Scheme 1 (5 pages, print/PDF). See any current masthead page for ordering information and Web access instructions.

JA9823464

---

[29] Buxton, G. V.; Djouider, F. *J. Chem. Soc., Faraday Trans.* **1996**, *92*, 4173−4176.