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# Reactions of Thiyl Radicals with Transition-Metal Complexes

**Patrick Huston, James H. Espenson,* and Andreja Bakac***

*Contribution from the Ames Laboratory and the Department of Chemistry, Iowa State University, Ames, Iowa 50011.* *Received May 18, 1992*

**Abstract:** Reactions of thiyl radicals ($RS^•$) were studied in aqueous solution by laser flash photolysis. Alkyl radicals, which were used to generate the thiyl radicals, were produced by the photohomolysis of the cobalt–carbon bond of $RCo([14]aneN_4)(H_2O)^{2+}$ complexes ($R = CH_3, C_2H_5$). These carbon-centered radicals abstract hydrogen atoms from thiols ($C_2H_5SH$, CysSH, or GSH), generating thiyl radicals. Thiyl radicals readily oxidize a variety of reduced transition-metal complexes. Kinetic and product studies were carried out, particularly for the ethylthiyl radical, to elucidate the mechanisms involved. Reactions of ethylthiyl radicals with inner-sphere reagents lead to metal–sulfur bond formation, and reactions with outer-sphere reagents produce thiolate ions and oxidized metal complexes. Ethylthiyl radicals also react with $RML_5^{2+}$ complexes (M = Co or Cr; L = $H_2O$ or tetraazamacrocycles). When $R = C_2H_5$, the thiyl radicals abstract a $\beta$-hydrogen atom, generating ethylene as a product. However, when $R = CH_3$, the reaction is an $S_H2$ substitution at carbon and $C_2H_5SCH_3$ is formed.

## Introduction

Thiyl radicals are intermediates in the oxidation of thiols to disulfides. These sulfur-centered radicals have been shown to be produced in biological systems in the reactions of oxidative enzymes with thiols.[1] The technique of pulse radiolysis has most often been used to generate thiyl radicals for chemical studies. The reactions responsible are those of $H^•$ or $^•OH$ with thiols (eqs 1 and 2). With alcohols present, hydroxyalkyl radicals are

$$H^• + RSH \rightarrow H_2 + RS^• \tag{1}$$

$$^•OH + RSH \rightarrow H_2O + RS^• \tag{2}$$

$$^•OH + CH_3OH \rightarrow H_2O + {}^•CH_2OH \tag{3}$$

$$^•CH_2OH + RSH \rightleftarrows CH_3OH + RS^• \tag{4}$$

generated (eq 3). They abstract a hydrogen atom from a thiol in the so-called repair reaction (eq 4).[2,3] This reaction is utilized in biological systems to protect against radiation damage and against naturally occurring radicals. Studies of the repair reaction involving a variety of carbon-centered radicals with thiols such as cysteine (CysSH), glutathione (GSH), cysteamine, and mercaptoethanol have been carried out previously by pulse radiolysis. The repair reaction typically has rate constants $k_4$ on the order of $10^7$–$10^9$ L mol$^{-1}$ s$^{-1}$. The sulfur–hydrogen bond dissociation enthalpy in alkanethiols is 88 kcal mol$^{-1}$ and is independent of the length and configuration of the alkyl chain.[4] Thus, alkylthiyl radicals are able to abstract hydrogen in the reverse of the repair reaction. This reverse reaction generally occurs much more slowly, with $k_{-4}$ typically in the range of $10^3$–$10^4$ L mol$^{-1}$ s$^{-1}$, depending on how strongly the C–H bond is activated.[5]

Thiyl radicals have also been generated by direct UV photolysis of disulfides. However, this may lead to cleavage of either the S–S or a C–S bond (eqs 5 and 6). For simple (methyl or ethyl)

$$RSSR + h\nu \rightarrow 2RS^• \tag{5}$$

$$RSSR + h\nu \rightarrow R^• + RSS^• \tag{6}$$

disulfides, reaction 6 was found to be unimportant; the cleavage of a C–S bond is apparently not very important unless particularly stable alkyl radicals are products.[6]

Thiyl radicals have been identified by spin trapping studies employing DMPO (5,5-dimethyl-1-pyrroline *N*-oxide) and TMPO (3,3,5,5-tetramethyl-1-pyrroline *N*-oxide).[7] The lack of nuclear spin in the main sulfur isotope, $^{32}S$, precludes obtaining any structural information from ESR. Thiyl radicals are not easily detectable by optical spectroscopy, having molar absorptivities of only several hundred around 300 nm.[8] For this reason, studies involving $RS^•$ have often been carried out in alkaline media (pH > 8), where the thiol is deprotonated and the highly colored disulfide radical anion is formed (eq 7).[8-10]

$$RS^• + RS^- \rightleftarrows RSSR^{•-} \tag{7}$$

Thiyl radicals are known to oxidize compounds such as ferrocytochrome *c*, NADH, ascorbate, phenothiazines, and organometallic substrates, such as boranes, phosphines, and phosphites.[11] The reduction potential for the $RS^•/RS^-$ couple has been estimated for $\beta$-mercaptoethanol to be 0.75 V vs NHE.[12] Recently, two studies in which thiyl radicals oxidized complexes of Cu(I) have been reported.[13] Cysteinyl radicals oxidize the $Cu^IL_2$ complex (L = cysteine) with a nearly diffusion-controlled rate constant ($k = 1.8 \times 10^9$ L mol$^{-1}$ s$^{-1}$). These studies were complicated by an equilibrium with $Cu_2L_3$ (eq 8), by acid–base equilibria, and by back reactions such as reaction 9.

$$2CuL_2 \rightleftarrows Cu_2L_3 + L \tag{8}$$

$$RSSR^{•-} + Cu^{II}L_y \rightarrow RSSR + Cu^IL_y \tag{9}$$

The presence of sulfur in the active site of many enzymes and its role in electron-transfer reactions make such studies important. Transition-metal–thiolate complexes may serve as models in un-

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derstanding the metal–thiol interactions in systems like non-heme iron–sulfur proteins.[14] We have recently reported a convenient method for generating and studying reactions of thiyl radicals.[15] Studies of these radicals with a variety of aqua– and organo–transition-metal complexes are described here.

## Experimental Section

**Materials.** All water used in this study was in-house distilled, deionized water, passed through a Millipore-Q purification system. All chemicals were used as received unless noted below. Solutions were degassed by being purged with water-saturated argon (99.99% pure, Air Products Corp.). Ethanethiol (Johnson Matthey Electronics) was purified by being passed through a column of neutral activated alumina (Brockman activity of 1, 80–200 mesh, Fisher). The following complexes were prepared by literature methods: $[RCo([14]aneN_4)(H_2O)](ClO_4)_2$ (R = $CH_3$, $C_2H_5$, $CD_3$, $C_2D_5$),[16] $V(H_2O)_6{}^{2+}$,[17] $Ti(H_2O)_6{}^{3+}$,[18] $(H_2O)_2Cr([15]aneN_4)^{2+}$,[19] $[Co(sep)]Cl_3$,[20] (*R*,*R*,*S*,*S*)-$[Ni([14]aneN_4)](ClO_4)_2$,[21] $(H_2O)_5CrC_2H_5{}^{2+}$,[22] $C_2H_5Cr([15]aneN_4)(H_2O)^{2+}$,[19] $[Co($*C-meso*-$Me_6[14]aneN_4)(H_2O)_2](ClO_4)_2$, and $[Co(Me_6[14]4,11\text{-}dieneN_4)(H_2O)_2](ClO_4)_2$.[23] *Caution! Perchlorate salts of transition-metal complexes, especially those of cyclam, are potentially explosive. Special care must be taken when working with these complexes.*

Stock solutions of *N*,*N*,*N′*,*N′*-tetramethyl-1,4-phenylenediamine (TMPD) (Aldrich) were prepared by addition of the solid to degassed water and were protected from light. Solutions of $Cr(H_2O)_6{}^{2+}$ in aqueous perchloric acid were prepared by reduction of solutions of $Cr(ClO_4)_3$ over zinc amalgam. Solutions of $Fe(H_2O)_6{}^{2+}$ were prepared in dilute aqueous perchloric acid, degassed, and placed over zinc amalgam. The concentrations of the solutions were determined spectrophotometrically by addition of an aliquot of the solution to excess 1,10-phenanthroline (Fisher), forming $Fe(phen)_3{}^{2+}$ ($\epsilon_{510} = 1.11 \times 10^4$ L mol$^{-1}$ cm$^{-1}$).[24] Solutions of $Ru(NH_3)_6(ClO_4)_2$ were prepared by dissolution of the trivalent complex in dilute perchloric acid, removal of oxygen with an argon purge, and reduction over zinc amalgam. Concentrations were determined spectrophotometrically at 275 nm ($\epsilon = 620$ L mol$^{-1}$ cm$^{-1}$).[25] Solutions of *trans*-$Co([14]aneN_4)(H_2O)_2{}^{2+}$ were prepared by mixing anaerobic solutions of $Co(ClO_4)_2$ and $[14]aneN_4$ (Aldrich). This was stirred until complex formation was complete (ca. 10 min), acidified to 0.05 M $HClO_4$, and transferred without contact with air to zinc amalgam. The complex was stored in ice and used within 1.5 h. Concentrations were determined spectrophotometrically at 460 nm ($\epsilon = 21.5$ L mol$^{-1}$ cm$^{-1}$).[26] The complex was added to cells buffered at pH 7.0 immediately before the flash photolysis experiment to minimize isomerization to the cis isomer.[27] Solutions of vitamin $B_{12r}$ were prepared by zinc amalgam reduction of vitamin $B_{12a}$ in neutral solution and used immediately.[28]

Thiolatochromium(III) complexes of the formula $(H_2O)_5CrSR^{2+}$ were prepared and purified using several different methods. An acidic aqueous solution containing $Cr(H_2O)_6{}^{2+}$ and excess diethyl disulfide was photolyzed at 254 nm using a Rayonet photochemical reactor with medium-pressure mercury lamps. The reaction mixture was placed on a cooled, degassed column of Sephadex C25 cation exchange resin. However, despite repeated washings, the purified sample, eluted with 0.5 M $NaClO_4$ in 0.01 M $HClO_4$, still contained disulfide. The second method was similar to the laser experiments. Similar concentrations of $CH_3Co([14]aneN_4)^{2+}$, $C_2H_5SH$, and $Cr(H_2O)_6{}^{2+}$ were used, but the scale was ~15 times larger. Upon cation exchange, the pure yellow thiolatochromium(III) complex was eluted with 0.5 M $NaClO_4$ in 0.01 M $HClO_4$. This method allowed small amounts of $CrSR^{2+}$ to be obtained pure. The last method employed was the reaction[29] of $Cr(H_2O)_6{}^{2+}$ with $(CH_3)_2CHSCo(dmgH)_2$, yielding $(H_2O)_5CrSCH(CH_3)_2{}^{2+}$. The 2-propanethiolatocobaloxime was prepared by a variation of the procedure for the MeS and PhS derivatives.[30] This method allowed preparations of $CrSR^{2+}$ to be carried out on a much larger scale.

**Analyses.** Chromium analyses were carried out on the thiolatochromium(III) complexes by oxidation to chromate ($\epsilon_{372} = 4830$ L mol$^{-1}$ cm$^{-1}$) in basic peroxide.[31] Cobalt(II) was determined as $Co(NCS)_4{}^{2-}$ ($\epsilon_{623} = 1842$ L mol$^{-1}$ cm$^{-1}$).[32] Ethanethiol and ethyl methyl sulfide were detected by the use of a Hewlett-Packard 5790A gas chromatograph with a Porapak Q column at 170 °C; methane, ethane, and ethylene were detected with a VZ-10 column at 50 °C.

The ratio of sulfur to chromium was determined by the use of inductively coupled plasma mass spectrometry (ICP/MS). First, the complex $(H_2O)_5CrSC_2H_5{}^{2+}$ was prepared by photolyzing a solution containing $CH_3Co([14]aneN_4)^{2+}$, $C_2H_5SH$, and $Cr^{2+}$ with visible light, as described above. The product mixture was placed on Sephadex C-25 cation exchange resin and eluted with 0.10 M LiBr/2 mM HBr. Sodium ions must be avoided because of the space charge effect; chlorine must be avoided because its mass-to-charge ratio is similiar to that of sulfur. The instrument[33] was a Sciex Elan Model 250 (Perkin-Elmer). The sample was introduced to the plasma by means of a Cetac U-5000 ultrasonic nebulizer. Sulfur was monitored at a mass-to-charge ratio of 34 and chromium at both 52 and 53.

**Laser Experiments.** Kinetic studies were carried out in 0.10 M $HClO_4$ except where noted. Reactions of the sulfur-centered radicals were measured by the use of a visible dye laser flash photolysis system described previously.[34] The excitation dye used was LD 490 (Exciton). Increases in absorbance due to formation of $ABTS^{\bullet-}$ were monitored at 650 nm ($\epsilon = 1.20 \times 10^4$ L mol$^{-1}$ cm$^{-1}$)[35] and those due to $TMPD^{\bullet+}$ at 565 nm ($\epsilon = 1.25 \times 10^4$ L mol$^{-1}$ cm$^{-1}$).[36] One or the other kinetic probe was used in all the experiments carried out by use of the dye laser.

The Nd:YAG laser system used here was an LKS.50 laser photolysis spectrometer from Applied Photophysics Limited. The laser itself was an SL800 system from Spectron Laser Systems. The fundamental wavelength output from the Nd:YAG laser (Q-switched) was frequency quadrupled by propagation through nonlinear harmonic generating crystals, yielding 266-nm light. The laser beam was set up perpendicular to the monitoring beam, a pulsed xenon lamp. The monitoring beam passed through the cell and through a grating monochromator to a five-stage photomultiplier tube. The signal was recorded on a PM3323 Philips digital oscilloscope interfaced to an Archimedes 420/1 computer. Using this system, diethyl disulfide was photolyzed at 266 nm in the presence of $Cr(H_2O)_6{}^{2+}$. The formation of $(H_2O)_5CrSR^{2+}$ was monitored directly at 280 nm without the use of a kinetic probe.

The rate law for the loss of radical in the presence of substrate, which was present in pseudo-first-order excess, is given by eq 10. However,

$$\frac{-d[RS^\bullet]}{dt} = 2k_{17}[RS^\bullet]^2 + k_s[\text{substrate}][RS^\bullet] \qquad (10)$$

as described previously,[26a,37] data were fitted to a first-order equation, as the production of only ~1 × 10$^{-6}$ M radical in a laser flash made the second-order component small. The validity of this approximation was confirmed using the kinetic simulation program KINSIM.[38] Three of the data sets were also subjected to a rigorous mixed first- and second-order kinetic analysis. The second-order rate constants $k_s$ obtained by the two methods agreed within 10%.

In two cases, the second stage, attributed to the reduction of $ABTS^{\bullet-}$ by reduced metal complex (see below), had rates comparable to those of

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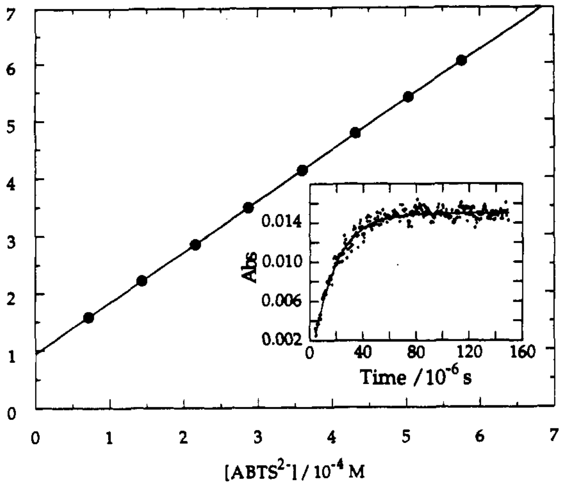

**Figure 1.** Plot of $k_{obs}$ against the concentration of ABTS$^{2-}$ for the reaction of CysS$^•$ with ABTS$^{2-}$ in 0.05 M phosphate buffer (pH 7.0) at ~25 °C. Inset shows the increase in absorbance at 650 nm with 5.04 × 10$^{-4}$ M ABTS$^{2-}$.

the first stage. Thus, data for the reactions of Fe(CN)$_6^{4-}$ and Cr([15]aneN$_4$)$^{2+}$ were fitted to a biexponential equation which yielded values of $k_s$ and $k_{11}$.

$$\mathrm{ABTS}^{•-} + \mathrm{L_6S}^{n} \rightarrow \mathrm{ABTS}^{2-} + \mathrm{L_6M}^{n+1} \qquad (11)$$

## Results

**Generation of Radicals.** One method for producing carbon-centered radicals (~1 × 10$^{-6}$ M) is the visible (490 nm) laser flash photolysis of aqueous solutions containing R'Co([14]aneN$_4$)(H$_2$O)$^{2+}$ (typically 1 × 10$^{-4}$ M), as in eq 12.[26a] With a

$$\mathrm{R'Co([14]aneN_4)^{2+}} + h\nu \rightarrow \mathrm{R'^{•}} + \mathrm{Co([14]aneN_4)^{2+}} \qquad (12)$$

$$\mathrm{R'^{•}} + \mathrm{RSH} \rightarrow \mathrm{R'H} + \mathrm{RS^{•}} \qquad (13)$$

$$\mathrm{R'^{•}} + \mathrm{R'^{•}} \rightarrow \mathrm{R'_2} \text{ or } \{\mathrm{R'(-H)} + \mathrm{R'H}\} \qquad (14)$$

$$\mathrm{RS^{•}} + \mathrm{ABTS^{2-}} \rightarrow \mathrm{RS^{-}} + \mathrm{ABTS^{•-}} \qquad (15)$$

water-soluble thiol present, such as ethanethiol, cysteine, or glutathione, the repair reaction was employed to generate thiyl radicals (eq 13). Because thiyl radicals are not highly colored,[8] two kinetic probes were used. Thiyl radicals were allowed to react with 2,2'-azinobis(3-ethylbenzothiazoline-6-sulfonate) ion (ABTS$^{2-}$) in a known reaction (eq 15)[39] to yield the highly colored radical anion ABTS$^{•-}$. Another probe used was TMPD, which is easily oxidized to the highly colored radical cation TMPD$^{•+}$. Thiyl radicals were observed to oxidize TMPD in neutral solution but not in acidic solution, as the protonated amine is much less easily oxidized.

**Kinetics.** The repair reaction was studied for methyl and ethyl radicals. With [ABTS$^{2-}$] ≫ [RSH] (10$^{-2}$ and 10$^{-4}$ M, typically), reaction 13 is rate limiting. Under these conditions, the observed rate constant is given by eq 16. The first term in eq 16 is due

$$k_{obs} = 2k_{14}[\mathrm{R'^{•}}] + k_{13}[\mathrm{RSH}] \qquad (16)$$

to carbon-centered radical self-reactions[40] and is small (generally <5% of $k_{obs}$). The second term, $k_{13}$[RSH], is due to the repair reaction. Thus, the pseudo-first-order rate constant is directly proportional to [RSH] and is independent of [ABTS$^{2-}$]. A plot of $k_{obs}$ vs [RSH] is linear, with a slope corresponding to the second-order rate constant $k_{13}$ and a small intercept due to radical self-reactions. The repair reaction was studied for $^•$CH$_3$ with ethanethiol, cysteine, and glutathione and for $^•$C$_2$H$_5$ with ethanethiol.[15] Methyl radicals abstract hydrogen atoms from ethanethiol with second-order rate constants of (4.0 ± 0.2) × 10$^7$ and (4.7 ± 0.2) × 10$^7$ L mol$^{-1}$ s$^{-1}$ at pH 1.0 and 7.0, respectively. Ethyl radicals react with ethanethiol at pH 7.0 with $k_{13}$ = (2.8 ± 0.1) × 10$^7$ L mol$^{-1}$ s$^{-1}$. Cysteine and glutathione have virtually identical reactivities toward $^•$CH$_3$ at pH 7.0 ($k_{13}$ = (7.4 ± 0.2) × 10$^7$ L mol$^{-1}$ s$^{-1}$ for CysSH and (7.1 ± 0.2) × 10$^7$ L mol$^{-1}$ s$^{-1}$ for GSH).

**Table I.** Rate Constants (~25 °C) for Reactions of Thiyl Radicals with ABTS$^{2-}$ (2,2'-Azinobis(3-ethylbenzothiazoline-6-sulfonate) ion[a]

| RS$^•$ | $k_{15}$/10$^7$ L mol$^{-1}$ s$^{-1}$ | pH |
|---|---|---|
| C$_2$H$_5$S$^•$ | 5.6 ± 0.2 | 1.0 |
| | 50 ± 4 | 7.0 |
| CysS$^•$ | 78 ± 2 | 4.0 |
| | 100[b] | 3.75 |
| | 8.8 ± 0.2 | 7.0 |
| | 50[b] | 7.1 |

[a] The pH was adjusted with phosphate buffer (pH 7.0) or by addition of HClO$_4$. Errors given are standard deviations in the data set as calculated by a nonlinear least-squares fitting program. [b] Reference 39.

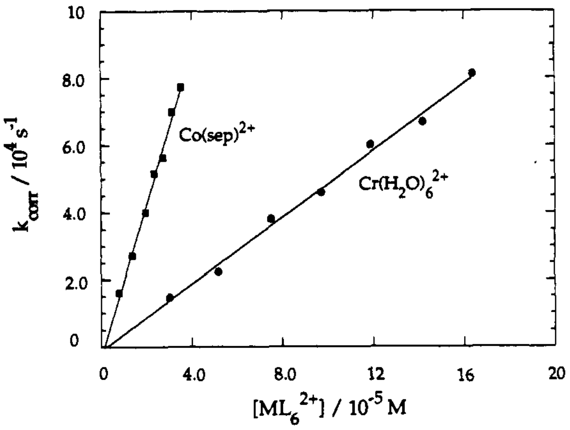

**Figure 2.** Observed pseudo-first-order rate constants at ~25 °C and pH 1.0 (HClO$_4$), corrected for radical self-reactions and the reaction of C$_2$H$_5$S$^•$ with ABTS$^{2-}$, varying linearly with [Co(sep)$^{2+}$] and [Cr(H$_2$O)$_6^{2+}$].

When [ABTS$^{2-}$] ≪ [RSH], reaction 13 is rapid and rates of reaction of RS$^•$ with ABTS$^{2-}$ can be determined. With 0.10 M ethanethiol present, reaction 13 is complete within 1 μs and self-reaction of the carbon-centered radicals (eq 14) is unimportant. With relatively low (10$^{-4}$ M) concentrations of ABTS$^{2-}$ present, reaction 17 must also be considered as a small, yet significant, contribution to the observed rate constant (eq 18). Thus,

$$\mathrm{RS^{•}} + \mathrm{RS^{•}} \rightarrow \mathrm{RSSR} \qquad (17)$$

$$k_{obs} = 2k_{17}[\mathrm{RS^{•}}] + k_{15}[\mathrm{ABTS^{2-}}] \qquad (18)$$

a plot of $k_{obs}$ vs [ABTS$^{2-}$] should be linear, with an intercept corresponding to the thiyl radical dimerization and a slope of the second-order rate constant for oxidation of ABTS$^{2-}$. Figure 1 shows such a plot for the reaction of cysteinyl radicals with ABTS$^{2-}$ at pH 7.0. The second-order rate constant for this reaction as well as for the oxidation by ethylthiyl radicals is listed in Table I, along with the two values for cysteinyl radical from previous studies.[15,39] TMPD was also oxidized by C$_2$H$_5$S$^•$, forming TMPD$^{•+}$ at pH 7.0, with a second-order rate constant of (2.6 ± 0.1) × 10$^9$ L mol$^{-1}$ s$^{-1}$.

Knowledge of the rate constants for reactions of thiyl radicals with intensely colored kinetic probes allows the study of their reactions with weakly colored transition-metal complexes to be carried out by the competition method. Typical conditions used were as follows: 1 × 10$^{-4}$ M CH$_3$Co([14]aneN$_4$)$^{2+}$, which generated ~1 × 10$^{-6}$ M $^•$CH$_3$ in the laser flash (eq 12); 0.10 M C$_2$H$_5$SH, to efficiently react with methyl radicals, generating C$_2$H$_5$S$^•$ (eq 13); ~6 × 10$^{-4}$ M ABTS$^{2-}$ or ~2 × 10$^{-5}$ M TMPD as a kinetic probe; and an appropriate amount of metal complex (eq 19) to make a measurable contribution to the observed

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**Table II.** Rate Constants (~25 °C) for Reactions of $C_2H_5S^•$ with Transition-Metal Complexes Obtained by Use of $ABTS^{2-}$ as a Kinetic Probe[a]

| | $k_{19}$/L mol$^{-1}$ s$^{-1}$ | pH |
|---|---|---|
| $Cr(H_2O)_6^{2+}$ | $(4.9 \pm 0.2) \times 10^8$ | 1.0 |
| $V(H_2O)_6^{2+}$ | $(6.5 \pm 0.3) \times 10^8$ | 1.0 |
| $Fe(H_2O)_6^{2+}$ | $(1.2 \pm 0.1) \times 10^6$ | 1.0 |
| $Cr([15]aneN_4)^{2+}$ | $(2.2 \pm 0.2) \times 10^8$ | 1.0 |
| $Co([14]aneN_4)^{2+}$ | $\sim 4.5 \times 10^8$ | 7.0[b] |
| $Co([Me_6[14]aneN_4)^{2+}$ | $(3.3 \pm 0.3) \times 10^8$ | 7.0[b] |
| $Co(Me_6[14]dieneN_4)^{2+}$ | $(3.1 \pm 0.3) \times 10^8$ | 7.0[b] |
| vitamin $B_{12r}$ | $(1.0 \pm 0.1) \times 10^9$ | 7.0[b] |
| $Ni([14]aneN_4)^{2+}$ | $<3 \times 10^6$ | 1.0 |
| $Cu([14]aneN_4)^{2+}$ | $<7 \times 10^5$ | 1.0 |
| $Co(sep)^{2+}$ | $(2.3 \pm 0.1) \times 10^9$ | 7.0[b] |
| $Ru(NH_3)_6^{2+}$ | $\sim 2 \times 10^9$ | 1.0 |
| $Fe(CN)_6^{4-}$ | $\sim 2 \times 10^7$ | 1.0 |
| $Fe(phen)_3^{2+}$ | $<1.6 \times 10^8$ | 1.0 |

[a] The pH was adjusted with phosphate buffer (pH 7.0) or by addition of $HClO_4$. Errors given are standard deviations in the data set as calculated by a nonlinear least-squares fitting program. [b] TMPD used as a kinetic probe.

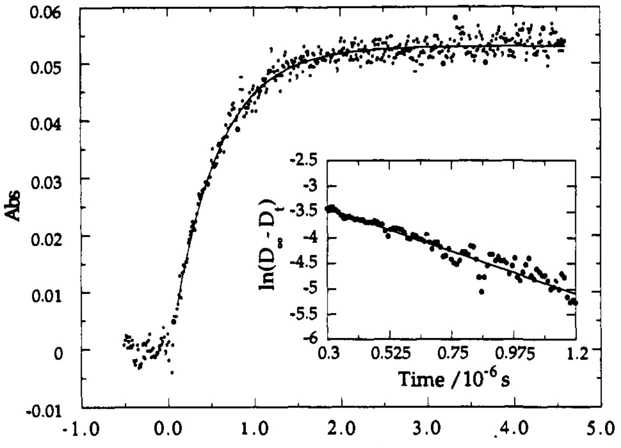

**Figure 3.** Increase in absorbance at 280 nm when diethyl disulfide was photolyzed at 266 nm in the presence of $4.12 \times 10^{-3}$ M $Cr(H_2O)_6^{2+}$ in 0.10 M $HClO_4$. Inset shows first-order plot for this trace.

pseudo-first-order rate constant (eq 20). The corrected first-order rate constant $k_{corr}$ is calculated according to eq 21. Thus, a plot

$$RS^• + L_6M^n \rightarrow L_5MSR^n + L \quad (19a)$$

$$RS^• + L_6M^n \rightarrow L_6M^{n+1} + RS^- \quad (19b)$$

$$k_{obs} = 2k_{17}[RS^•] + k_{15}[ABTS^{2-}] + k_{19}[L_6M^n] \quad (20)$$

$$k_{corr} = k_{obs} - (2k_{17}[RS^•] + k_{15}[ABTS^{2-}]) = k_{19}[L_6M^n] \quad (21)$$

of $k_{corr}$ vs $[L_6M^{n+}]$ is expected to be a straight line, with a slope of $k_{19}$ and a zero intercept. Such a plot is shown in Figure 2 for the reaction of $C_2H_5S^•$ with $Co(sep)^{2+}$ and $Cr(H_2O)_6^{2+}$. Each point is the average of 3–4 laser flash experiments. The rate constants for reactions of $C_2H_5S^•$ with a variety of reduced metal complexes are given in Table II. The macrocyclic cobalt(II) complexes precipitate in the presence of the required amount of $ABTS^{2-}$, so TMPD was used as the probe in those cases.

**Table III.** Rate Constants (~25 °C) for Reactions of $C_2H_5S^•$ with $RML_5^{2+}$ Complexes Obtained by Use of $ABTS^{2-}$ as a Kinetic Probe in 0.10 M $HClO_4$[a]

| | $k_{23}$/L mol$^{-1}$ s$^{-1}$ | products |
|---|---|---|
| $CH_3Cr(H_2O)_5^{2+}$ | $(3.4 \pm 0.4) \times 10^8$ | |
| $CH_3Co([14]aneN_4)(H_2O)^{2+}$ | $(2.4 \pm 0.2) \times 10^7$ | $C_2H_5SCH_3$ |
| $CD_3Co([14]aneN_4)(H_2O)^{2+}$ | $(2.7 \pm 0.2) \times 10^7$ | |
| $C_2H_5Cr(H_2O)_5^{2+}$ | $(9.7 \pm 0.5) \times 10^7$ | $C_2H_4$ |
| $C_2H_5Cr([15]aneN_4)(H_2O)^{2+}$ | $(5.9 \pm 0.5) \times 10^7$ | $C_2H_4$ |
| $C_2D_5Cr([15]aneN_4)(H_2O)^{2+}$ | $(1.8 \pm 0.1) \times 10^7$ | |
| $C_2H_5Co([14]aneN_4)(H_2O)^{2+}$ | $(1.1 \pm 0.1) \times 10^8$ | $C_2H_4$ |
| | $(1.2 \pm 0.1) \times 10^8$ | |
| $C_2D_5Co([14]aneN_4)(H_2O)^{2+}$ | $(4.5 \pm 0.4) \times 10^7$ | |
| $(CH_3)_2CHSCr(H_2O)_5^{2+}$ | $(1.2 \pm 0.1) \times 10^8$ | |

[a] Errors given are standard deviations in the data set as calculated by a nonlinear least-squares fitting program.

**Table IV.** Rate Constants (25 °C) for Reactions of $ABTS^{•-}$ with Reduced Metal Complexes in 0.10 M $HClO_4$[a]

| | $k_{11}$/L mol$^{-1}$ s$^{-1}$ |
|---|---|
| $Cr(H_2O)_6^{2+}$ | $(1.1 \pm 0.1) \times 10^8$ |
| $V(H_2O)_6^{2+}$ | $(2.6 \pm 0.1) \times 10^8$ |
| $Ti(H_2O)_6^{3+}$ | $(1.4 \pm 0.1) \times 10^5$ |
| $Ru(NH_3)_6^{2+}$ | $(2.2 \pm 0.2) \times 10^9$ |
| $Fe(CN)_6^{4-}$ | $\sim 2 \times 10^7$ |

[a] Errors given are standard deviations in the data set as calculated by a nonlinear least-squares fitting program.

Formation of ethanethiolatochromium(III) could be observed directly at 280 nm. With a Nd:YAG laser, diethyl disulfide was photolyzed at 266 nm in the presence of $Cr(H_2O)_6^{2+}$. This method allowed much higher concentrations of $Cr(H_2O)_6^{2+}$ to be used, as it is capable of measuring much higher rates. At 280 nm a single exponential increase in absorbance was observed (Figure 3). The value of $k_{obs}$ was directly proportional to $[Cr(H_2O)_6^{2+}]$, since under these conditions the first term on the right-hand side of eq 22 can be ignored. The second-order rate constant for the

$$k_{obs} = 2k_{17}[RS^•] + k_{19}[Cr^{2+}] \quad (22)$$

reaction of ethylthiyl radicals with $Cr(H_2O)_6^{2+}$ obtained by this method was $(4.0 \pm 0.2) \times 10^8$ L mol$^{-1}$ s$^{-1}$, in good agreement with the value obtained using $ABTS^{2-}$ as a kinetic probe, $(4.9 \pm 0.2) \times 10^8$ L mol$^{-1}$ s$^{-1}$.

Reactions of ethylthiyl radicals with organochromium(III) and organocobalt(III) complexes (eq 23) were examined at pH 1.0

$$C_2H_5S^• + RML_5^{2+} \rightarrow \text{products} \quad (23)$$

with $ABTS^{2-}$ as a probe. The rate constants are listed in Table III, along with the products detected in certain cases. The second-order rate constants fall in the range of $(1.8–34) \times 10^7$ L mol$^{-1}$ s$^{-1}$. For the $RCo([14]aneN_4)(H_2O)^{2+}$ complexes, the reaction is that of $C_2H_5S^•$ with the organocobalt complex itself, which also is the source of the alkyl radical from which the thiyl radical results. The dual role of alkyl cobalt leads to certain complications. As the concentration of $RCo([14]aneN_4)(H_2O)^{2+}$ was varied, the laser power was adjusted to prevent significant changes in radical concentration. To account for radical dimerization (eq 17) under these conditions of relatively high radical concentration, the data were fitted to a mixed first- and second-order equation.

When reactions of thiyl radicals with $Cr(H_2O)_6^{2+}$, $Cr([15]aneN_4)(H_2O)_2^{2+}$, $V(H_2O)_6^{2+}$, $Ti(H_2O)_6^{3+}$, $Fe(CN)_6^{4-}$, $Co(sep)^{2+}$, or $Ru(NH_3)_6^{2+}$ were studied with $ABTS^{2-}$ as a kinetic probe, biexponential kinetics were observed. An increase in absorbance at 650 nm, due to the formation of $ABTS^{•-}$ (eq 15), was followed by a decrease in absorbance, due to the reduction of $ABTS^{•-}$ by the metal complex (eq 11). The second stage was studied by varying the concentration of metal ion and employing relatively high concentrations of $ABTS^{2-}$ ($10^{-3}$ M) so that the first stage was very fast. The summary of the rate constants for eq 11 is given in Table IV.

**Product Studies.** Ethanethiolatochromium(III) was prepared by visible light photolysis (275-W sunlamp) of 15 mL of $2.8 \times 10^{-4}$ M $CH_3Co([14]aneN_4)(H_2O)^{2+}$, 0.10 M $C_2H_5SH$, and $1 \times 10^{-3}$ M $Cr(H_2O)_6^{2+}$ at pH 1.0. The product was purified by cation exchange chromatography at ~5 °C. The half-life of $(H_2O)_5CrSC_2H_5^{2+}$ was ~30 min in 0.10 M $HClO_4$ at 25 °C. The UV spectrum exhibits $\lambda_{max} = 280$ nm ($\epsilon = 7400 \pm 100$ L mol$^{-1}$ cm$^{-1}$). The chromium-to-sulfur ratio was determined by ICP/MS to be 1.1:1; consistent with the formula written.

To check for reaction 19b, disulfide was photolyzed at 254 nm in the presence of the metal complex. With either $V(H_2O)_6^{2+}$ or $Fe(H_2O)_6^{2+}$ present, thiol was detected as a product using GC. However, no thiol was found when diethyl disulfide was photolyzed with $Cr(H_2O)_6^{2+}$ present.

In the reactions of $C_2H_5S^\bullet$ radicals with $RML_5^{2+}$ complexes, organic products were detected gas chromatographically. When R = $C_2H_5$, determinations of ethylene yielded the ratio $[C_2H_4]$:[Co(II)] of 0.8:2. In the reaction of $C_2H_5S^\bullet$ with $CH_3Co([14]aneN_4)^{2+}$, the ratio of $[C_2H_5SCH_3]$:[Co(II)] was determined to be 0.9:2. Methane (or ethane) was produced from the repair reaction when the radical precursor was $CH_3Co([14]aneN_4)^{2+}$ (or $C_2H_5Co([14]aneN_4)^{2+}$). Some ethane was also detected with $C_2H_5Cr(H_2O)_5^{2+}$, due to significant heterolysis of this complex on the timescale of the experiment (~5 min).

## Discussion

The complexes $RCo([14]aneN_4)^{2+}$, with R = $CH_3$, $C_2H_5$, etc., are known to generate carbon-centered radicals when photolyzed with visible (490 nm) light. This system has been employed for studying the reactions of alkyl radicals with metal complexes.[26a] Here, the carbon-centered radicals have been used simply as a means for generating sulfur-centered radicals.

**Repair Reaction.** Probably the most important reaction involving thiyl radicals is the repair reaction (eq 13).[2,3] The use of $RCo([14]aneN_4)^{2+}$ complexes allows a series of primary hydrocarbon radicals to be generated photochemically, and reactions of alkyl radicals with thiols[15] may be conveniently studied. Glutathione is the most important thiol to include in repair reaction studies because of its high intracellular levels in the body ([GSH] $\leq$ 0.01 M).[41]

Almost no steric effect is observed in the abstraction of hydrogen atoms from ethanethiol by methyl and ethyl radicals. This is consistent with a previous report on hydrogen abstraction from thiophenol by primary, secondary, and tertiary radicals.[42] Cysteine and glutathione were found to have virtually the same rate of repair with methyl radicals. All of the repair reaction rate constants determined here and virtually all the literature data[2,3] establish that a "typical" value for $k_{13}$ lies in the range of $10^7$–$10^8$ L mol$^{-1}$ s$^{-1}$.

The reverse of the repair reaction has been studied for alcohols and typically occurs with rate constants of $10^3$–$10^4$ L mol$^{-1}$ s$^{-1}$.[5] For this reason, cosolvents were avoided in the present work and studies were carried out in strictly aqueous solution. Thiols were chosen on the basis of their solubility, and most of the studies with metal complexes were carried out with ethanethiol, which has a solubility in water at 20 °C of 0.112 M, more than enough to react efficiently with virtually all of the alkyl radicals.

**Kinetic Probes.** The thiyl radicals are difficult to observe directly, and studies have often been carried out in the presence of excess thiolate. Under these conditions, the highly colored disulfide radical anions form readily (eq 7). However, the p$K_a$ values for most thiols are $\geq$8, which means that $RSSR^{\bullet-}$ does not form in neutral and acidic solutions. Under the conditions in which $RSSR^{\bullet-}$ does form, the system may become kinetically complex because it is sometimes difficult to separate reactions of thiyl radicals from those of $RSSR^{\bullet-}$. Thus, for the study of metal complexes in acidic and neutral aqueous solution, we turned to $ABTS^{2-}$ and TMPD as kinetic probes that are stable in the pH region of 1–7.

The oxidation of $ABTS^{2-}$ by cysteinyl radicals was studied at pH 4, and the second-order rate constant obtained was acceptably close to the value reported at pH 3.75 (see Table I).[39a] The reaction of $C_2H_5S^\bullet$ with $ABTS^{2-}$ was also studied under the same conditions as the reactions with metal complexes (0.10 M $HClO_4$). Under these conditions, the reaction is much slower, probably because the protonated form, $HABTS^-$, is more difficult to oxidize than the unprotonated form (p$K_a$ = 2.2).

As mentioned above, the cobalt(II) complexes used in this study precipitated with $ABTS^{2-}$. Thus, another probe, TMPD, was also used. TMPD is easily oxidized, having $E^\circ$ = 0.27 V vs NHE at pH 7.[43] The radical cation $TMPD^{\bullet+}$ is stable for more than a week. Ethylthiyl radicals were found to oxidize TMPD in a diffusion-controlled process.[15] The mechanism of oxidation is most likely electron transfer, as other radicals react at similar rates and a reaction involving hydrogen transfer would be slower. Other studies have shown that TMPD is oxidized by the radical $^\bullet CH_2CHO$[43] with a rate constant of 2.1 × $10^9$ L mol$^{-1}$ s$^{-1}$ and by substituted methylperoxyl radicals at rates that vary from $10^6$ to $10^9$ L mol$^{-1}$ s$^{-1}$, increasing as the electron-withdrawing capacity of the substituent on the methyl group increases.[44] The lack of reaction at pH 1 is due to protonation of TMPD, which has a p$K_a$ = 5.3.[45] The discovery of this simple reaction may actually be a very significant portion of this work. TMPD may be used to easily detect thiyl radicals and follow their reactions at physiological pH. The very high rate constant for this reaction means that even very low concentrations of TMPD will be effective.

**Reduced Metal Complexes.** We have examined reactions between $C_2H_5S^\bullet$ and $M(H_2O)_6^{2+}$ (M = Cr, V, or Fe) at pH 1 using $ABTS^{2-}$ as a kinetic probe. The reactions of thiyl radicals with $Cr(H_2O)_6^{2+}$ occur about twice as fast as those of alkyl radicals.[26a] The dimerization reactions of thiyl radicals[9] are also slightly faster than those of alkyl radicals.[40] The reaction with $Cr(H_2O)_6^{2+}$ was expected to be an inner-sphere process (eq 19a) and to form stable thiolatochromium(III) as a product. Two similar compounds that are known to be stable for hours are $(H_2O)_5CrSC_6H_4NH_3^{3+}$ and $(H_2O)_5CrSC_6H_4N(CH_3)_3^{3+}$.[46] Also known is the mercaptochromium(III) ion $(H_2O)_5CrSH^{2+}$.[47] Indeed, $Cr(H_2O)_6^{2+}$ was observed to react with $C_2H_5S^\bullet$ by an inner-sphere mechanism. When disulfide was photolyzed in the presence of $Cr(H_2O)_6^{2+}$, an increase in absorbance at wavelengths below 300 nm was observed, suggesting Cr–S bond formation. No free thiol was detected as a product, as would be expected from an outer-sphere reaction (eq 19b). Ethanethiolatochromium(III), which was isolated by cation exchange chromatography, exhibits an absorption band at 280 nm, characteristic of a Cr–S MLCT band.[46-48] This work has shown that generating thiyl radicals in the presence of $Cr(H_2O)_6^{2+}$ is an effective method of preparing the thiolatochromium(III) complexes, since $Cr(H_2O)_6^{2+}$ does not react directly with simple (methyl or ethyl) disulfides.

The $Fe(H_2O)_6^{2+}$ reaction with $C_2H_5S^\bullet$ is inferred also to go by an inner-sphere mechanism, since its rate constant is comparable to that for the reaction of $Br_2^-$ with $Fe(H_2O)_6^{2+}$ (3.6 × $10^6$ L mol$^{-1}$ s$^{-1}$), which is known to be an inner-sphere process.[49] The aquation rate constants for $Fe(H_2O)_5X^{2+}$, typically 10–$10^2$ L mol$^{-1}$ s$^{-1}$, are small on the timescale of the oxidation of $Fe(H_2O)_6^{2+}$ by ethylthiyl radicals. However, the presumed initial product of the reaction, $(H_2O)_5FeSC_2H_5^{2+}$, was not observed, probably due to low extinction coefficients.

Oxidation of $V(H_2O)_6^{2+}$ by alkyl radicals in aqueous solution occurs with rate constants in the range of (1–6) × $10^5$ L mol$^{-1}$ s$^{-1}$ and shows little dependence on the steric bulk of the radical. The mechanism suggested for this reaction involves radical attack at a trigonal face of $V(H_2O)_6^{2+}$. This allows electron transfer to occur, yielding a transient seven-coordinate intermediate, $(H_2O)_6VR^{2+}$, which undergoes protonolysis to yield V(III) and alkane.[17] It seems likely that the mechanism for the oxidation of $V(H_2O)_6^{2+}$ by $C_2H_5S^\bullet$ again involves radical attack at a trigonal face of $V(H_2O)_6^{2+}$, where a bond to sulfur can be formed as the electron is transferred. However, the thiyl radical reacts much more rapidly than the alkyl radical. The large sulfur-centered radical may be better able to provide orbital overlap and thus facilitate electron transfer. The proposed intermediate $(H_2O)_6VSR^{2+}$ was not observed directly, which may be attributed to either a short lifetime or low extinction coefficients.

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Table V. Kinetic Data for Hydrogen Atom Abstraction by Alkyl and Thiyl Radicals

| substrate | radical | $k$/L mol$^{-1}$ s$^{-1}$ | ref |
|---|---|---|---|
| $C_2H_5OH$ | $^\bullet CH_3$ | $5.9 \times 10^2$ | 60a |
| $C_2H_5OH$ | $PenS^\bullet$ | $2.3 \times 10^3$ | 5c |
| $(CH_3)_2CHOH$ | $^\bullet CH_3$ | $3.4 \times 10^3$ | 60a |
| $(CH_3)_2CHOH$ | $CysS^\bullet$ | $2.0 \times 10^4$ | 5c |
| $(CH_3)_2CHOH$ | $GS^\bullet$ | $1.2 \times 10^4$ | 5c |
| $(CH_3)_2CHOH$ | $PenS^\bullet$ | $1.4 \times 10^4$ | 5b,5c |
| $HSCH_2(CHOH)CH_2SH$ | $^\bullet CH_2OH$ | $6.5 \times 10^7$ | 60b |
| $HSCH_2(CHOH)CH_2SH$ | $^\bullet SCH_2CH_2OH$ | $2.0 \times 10^7$ | 60b |
| $[4.4.4]^{\bullet +}$ [a] | $^\bullet CH_3$ | $1.6 \times 10^9$ | 57 |
| $[4.4.4]^{\bullet +}$ [a] | $^\bullet SC(CH_3)_3$ | $1.6 \times 10^9$ | 57 |
| $C_2H_5Cr([15]aneN_4)(H_2O)^{2+}$ | $C_2H_5S^\bullet$ | $(5.9 \pm 0.5) \times 10^7$ | this work |
| $C_2H_5Co([14]aneN_4)(H_2O)^{2+}$ | $C_2H_5S^\bullet$ | $(1.1 \pm 0.1) \times 10^8$ | this work |
| $C_2H_5Cr(H_2O)_5^{2+}$ | $^\bullet CH_3$ | $\leq 1 \times 10^6$ | this work |
| $C_2H_5Co(dmph)^{2+}$ | $^\bullet CH_3$ | $\leq 1 \times 10^6$ | 58 |
| $C_6H_5CH(CH_3)_2$ | $^\bullet CCl_3$ | 41 | 63b |
| $C_6H_5CH(CH_3)_2$ | $p\text{-}ClC_6H_4S^\bullet$ | $1.2 \times 10^3$ | 63a |

[a] $[4.4.4]^{\bullet +}$ = 1,6-diazabicyclo[4.4.4]dodecane radical cation.

The macrocyclic chromium complex $Cr([15]aneN_4)(H_2O)_2^{2+}$ reacts with $C_2H_5S^\bullet$ with a rate constant approximately one-half that of the hexaaquachromium(II) complex. This is similar to the small difference in reactivities these complexes exhibit toward alkyl radicals.[50] This difference may be attributed to a statistical effect, on the basis of the number of replaceable water molecules, or to the macrocycle partially blocking the approach of the radical.

In the reactions of ethylthiyl radicals with $(H_2O)_2CoL^{2+}$ complexes, where L = $[14]aneN_4$, $Me_6[14]aneN_4$, or $Me_6[14]4,11$-diene, the rate constants all fall in a very narrow range. Again, the thiyl radicals are observed to react faster than alkyl radicals.[37a,51] The faster reaction of $C_2H_5S^\bullet$ with vitamin $B_{12r}$ is probably due to the larger driving force and to the fact that the cobalt of vitamin $B_{12r}$, being pentacoordinate in neutral solution, need not engage in a substitution step.[52] The reactions of thiyl radicals with these cobalt(II) complexes are expected to yield thiolatocobalt(III) complexes. A number of mono- and bidentate thiolatocobalt(III) complexes are known to be stable, including complexes such as $Co(dmgH)_2(SC_6H_5)$ and $Co(en)_2(SCH_2CH_2NH_2)^{2+}$.[30] However, the formation of thiolatocobalt(III) complexes was not observed directly, despite the expected LMCT band in the 250–300-nm region.[48] This band should occur at lower energy (and thus be more easily observable) than the thiolatochromium(III) LMCT band, since cobalt(III) is a better oxidant than Cr(III). It may be that these cobalt(III) complexes are simply less strongly absorbing.

The complex $Co(sep)^{2+}$ is oxidized by $C_2H_5S^\bullet$ with a diffusion-controlled rate constant. The cagelike structure of $Co(sep)^{2+}$ requires that this involve an outer-sphere oxidation of the cobalt, generating $Co(sep)^{3+}$ and thiolate ion (eq 19b). The reactions of $C_2H_5S^\bullet$ with $Fe(CN)_6^{4-}$ and with $Ru(NH_3)_6^{2+}$ also proceed by outer-sphere electron transfer. In these cases, the reaction of $ABTS^{\bullet -}$ with the reduced metal complex is fast enough to prevent accurate determinations of these rate constants, due to small absorbance changes and limited concentration ranges possible.

An outer-sphere reagent that did not react measurably with $C_2H_5S^\bullet$ was $Fe(phen)_3^{2+}$, probably due to lack of driving force ($E°$ for $Fe(phen)_3^{3+/2+}$ = 1.09 V).[53] The upper limit for this rate constant is relatively high, because higher concentrations of $Fe(phen)_3^{2+}$ significantly blocked the excitation light.

**Reactions of $RML_5^{2+}$ Complexes.** From the rate constants listed in Table III, it is seen that thiyl radicals react with organochromium(III) and organocobalt(III) complexes with rate constants on the order of $10^7$–$10^8$ L mol$^{-1}$ s$^{-1}$. Such a reaction was suggested as one step in the reaction of thiols with methylcobalamin (eq 24).[54] This type of homolytic displacement reaction also was considered as a possible mechanism in the reactions of alkyl- and benzylcobaloximes with disulfides (eq 25).[55] A similar reaction occurs with *cis*-$PtR_2X_2$ (R = $CH_3$, $C_2H_5$, $(CH_3)_3SiCH_2$, or $PhCH_2$), where the homolytic displacement of $R^\bullet$ (eq 26) was demonstrated by ESR.[56]

$$CH_3Co(III) + {}^-O_3SCH_2CH_2S^\bullet \rightarrow Co(II) + {}^-O_3SCH_2CH_2SCH_3 \quad (24)$$

$$ArS^\bullet + RCo(dmgH)_2py \rightarrow ArSR + Co(dmgH)_2py \quad (25)$$

$$PhS^\bullet + PtR_2X_2 \rightarrow PtR(SPh)X_2 + R^\bullet \quad (26)$$

Reactions of $C_2H_5S^\bullet$ radicals with $C_2H_5ML_5^{2+}$ complexes (M = Co or Cr) exhibit a significant kinetic isotope effect and produce ethylene quantitatively. Both findings suggest a hydrogen abstraction by the thiyl radicals (eq 27). This reaction may be compared to the reverse of the repair reaction (eq 28). The rate

$$C_2H_5S^\bullet + C_2H_5M^{2+} \rightarrow C_2H_5SH + C_2H_4 + M^{2+} \quad (27)$$

$$R'S^\bullet + RH \rightarrow R'SH + R^\bullet \quad (28)$$

constants for reaction 28 depend strongly on the activation of the C–H bond. In cases such as thiyl radicals abstracting hydrogen atoms from alcohols, the rate constant is typically on the order of $10^3$–$10^4$ L mol$^{-1}$ s$^{-1}$.[5b] However, with highly activated C–H bonds, the rate constant may be as high as $10^9$ L mol$^{-1}$ s$^{-1}$.[57] Thus, the rate constants of ~$10^8$ L mol$^{-1}$ s$^{-1}$ obtained for reaction 27 suggest that the C–H bonds in these complexes are significantly activated.

Thermodynamically, alkyl radicals should be even better able to abstract a hydrogen atom, but this does not appear to be the case. In fact, alkyl radicals react with organocobaloximes by homolytic displacement at carbon (eq 29) with rate constants of ~$1 \times 10^7$ L mol$^{-1}$ s$^{-1}$.[58] No hydrogen atom abstraction is observed. The complex $CH_3Ni([14]aneN_4)^{2+}$ reacts with methyl radicals (but not with ethyl radicals) in a similar manner (eq 30).[59]

$$R^\bullet + R'Co(dmgH)_2OH_2 \rightarrow RR' + Co(dmgH)_2OH_2 \quad (29)$$

$$^\bullet CH_3 + CH_3NiL^{2+} \rightarrow C_2H_6 + NiL^{2+} \quad (30)$$

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In this study, we looked for the reaction of $^{\bullet}CH_3$ with $C_2H_5Cr(H_2O)_5^{2+}$, using $ABTS^{\bullet-}$ as a kinetic probe. No reaction was observed, and an upper limit on the rate constant of $1 \times 10^6$ L mol$^{-1}$ s$^{-1}$ was obtained.

There are a few cases in which hydrogen atom abstractions by alkyl and thiyl radicals may be directly compared (Table V).[5b,57,60] From the data, one concludes that the C–H bonds in $C_2H_5ML_5^{2+}$ complexes are strongly activated, which allows thiyl radicals to abstract hydrogen atoms with ease. The ethyl complexes react with $C_2H_5S^{\bullet}$ with rate constants that are 3–4 orders of magnitude larger than those for hydrogen abstraction by similar thiyl radicals from a secondary alcohol.[5b] While this reactivity is remarkable, one must also note that the increase in reactivity toward $^{\bullet}CH_3$ is substantially less and possibly absent. The high reactivity of $C_2H_5ML_5^{2+}$ toward $C_2H_5S^{\bullet}$ thus appears to reside mainly with the radical and not (or much less) with the alkyl complexes.

This is not the first study to suggest that thiyl radicals are better at hydrogen atom abstraction than are hydrocarbon radicals. Product studies have shown that compounds like 9,10-dihydroanthracene react rapidly with *n*-octylthiyl radicals but only slowly with methylbenzyl radicals.[61] Triphenylmethylthiyl radicals were found to be more reactive than $^{\bullet}CCl_3$ in abstraction from toluene, ethylbenzene, tetralin, diphenylmethane, and dihydroanthracene (relative rates were determined).[62] Also, the *p*-chlorophenylthiyl radical was reported to abstract hydrogen from cumene about 30 times faster than $^{\bullet}CCl_3$ (Table V).[63]

Thiyl radicals have been noted to be particularly electrophilic and are likely to add to centers of relatively high electron density, such as $\pi$ systems and nonbonded electron pairs at heteroatoms.[2,64] This electrophilicity may be enhanced by the ability of sulfur to use d orbitals to accommodate negative charge. Thus, $RS^{\bullet}$ radicals add to disulfides to form an intermediate radical adduct[65] (eq 31), and to olefins (eq 32).[2] The *tert*-butylthiyl radical adds to

$$RS^{\bullet} + R'SSR \rightarrow [R'SS(SR)R']^{\bullet} \rightarrow R'SSR + R'S^{\bullet} \qquad (31)$$

$$RS^{\bullet} + R'CH{=}CH_2 \rightarrow {}^{\bullet}CH(R')CH_2SR \qquad (32)$$

1-octene with a rate constant of $1.9 \times 10^6$ L mol$^{-1}$ s$^{-1}$.[11d] However, $^{\bullet}CH_3$ reacts much more slowly with simple alkenes such as ethylene, propylene, and 1-butene, having rate constants in the range of $(4.9\text{–}30) \times 10^3$ L mol$^{-1}$ s$^{-1}$.[60a] Pryor and co-workers suggested that the polarizability of the radical may be an important factor in determining the electrophilicity of the radical in hydrogen abstractions.[66] Thus, the difference in polarizabilities in thiyl and alkyl radicals may account for their different abilities to abstract hydrogen.

For the reactions of $C_2H_5S^{\bullet}$ with $CH_3ML_5^{2+}$ (M = Co or Cr) there is no kinetic isotope effect (Table III). This suggests a change in mechanism that may involve reactions 33 or 34. In

$$C_2H_5S^{\bullet} + CH_3M^{2+} \rightarrow C_2H_5S^-, M^{2+} + {}^{\bullet}CH_3 \qquad (33)$$

$$C_2H_5S^{\bullet} + CH_3M^{2+} \rightarrow C_2H_5SCH_3 + M^{2+} \qquad (34)$$

reaction 33, methyl radical is formed, and under the conditions employed here, methyl radical would rapidly react with thiol to generate $C_2H_5S^{\bullet}$ radical. This would result in a chain reaction in which a small amount of radical formed in the laser flash would consume a relatively large amount of $CH_3ML_5^{2+}$. This was checked by photolyzing the complex $CH_3Co([14]aneN_4)^{2+}$. However, the same amount of $CH_3Co([14]aneN_4)^{2+}$ was consumed in the presence and in the absence of ethanethiol, ruling out this mechanism. Thus, we propose reaction 34, a bimolecular homolytic substitution ($S_H2$) at the saturated carbon atom. In fact, ethyl methyl sulfide was found to be formed quantitatively in the reaction of $C_2H_5S^{\bullet}$ with $CH_3Co([14]aneN_4)^{2+}$. This is in agreement with the proposed mechanism for the reaction of thiols with methylcobalamin (eq 24).[54a]

The similarity of the rate constants for the reactions of $C_2H_5S^{\bullet}$ with methyl and ethyl complexes, Table III, appears to be coincidental. If methyl and ethyl complexes reacted by the same mechanism, then the methyl complexes would be expected to be much more reactive ($S_H2$)[67] or much less reactive (H-abstraction) than the ethyl complexes. In fact, it is just because of the vast differences in the reactivity order in the two types of reactions that such a straightforward change in mechanism takes place and can be recognized in the reactions with thiyl radicals.

The method of generating and studying reactions of thiyl radicals reported here may be applied to the study of the biologically significant cysteinyl and glutathionyl radicals without pulse radiolysis equipment. It is particularly suited to the study of thiyl radicals with metal complexes and should prove useful in many inorganic and bioinorganic studies. In addition, some of the reactions reported here may be useful in the synthesis of thiolato–transition-metal complexes.

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