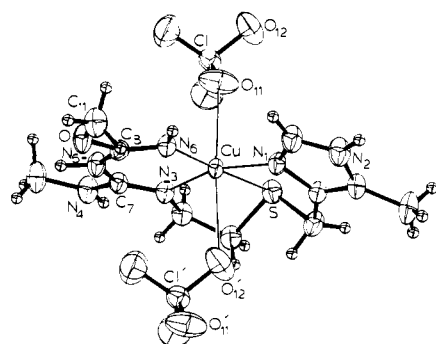**Figure 2.** Perspective ORTEP drawing for one of the octahedral [Cu^{II}-(1)$_2$]$^{2+}$ (4) subunits of Figure 1. Nonhydrogen atoms are represented by thermal vibration ellipsolids drawn to encompass 50% of the electron density; hydrogen atoms are represented by arbitrarily small spheres for purposes of clarity. Atoms labeled with a prime are related to those without a prime by the crystallographic inversion center at the Cu atom.

Figure 3. Perspective ORTEP drawing for one of the octahedral [Cu^{II}-(3)(ClO$_4$)]$^{1+}$ subunits in the cationic solid-state [Cu^{II}(3)(ClO$_4$)]$_n^{n+}$ polymer of 5. Nonhydrogen atoms are represented by thermal vibration ellipsoids drawn to encompass 50% of the electron density; hydrogen atoms are represented by arbitrarily small spheres for purposes of clarity. Atoms of the perchlorate group labeled with a prime are related to those labeled without a prime by translation of one unit cell along $\bar{b}$.

greater in-plane crystal field strength. This is also confirmed by the appliction of the rule of average environment to the positions of the d–d bands of 5.[18]

The X-ray diffraction studies of 4 and 5 reveal a solid-state structure composed of polymeric cationic Cu(II) complexes and anionic perchlorate groups. The cationic unit of 4 is an infinite polymer (Figure 1) of centrosymmetric octahedral Cu(II) subunits like that shown in Figure 2 which are generated by a bridging tridentate cimetidine ligand. The cationic unit of 5 is also an infinite polymer (Figure 3) which is formed by bidentate perchlorate anions bridging nearly square-planar dicationic Cu(II) complexes of the neutral tetradentate methoxyimine ligand (3). The bridging perchlorate Cu–O interactions in 5 are weak with bond lengths of 2.505 (6) and 2.805 (7) Å.

The planar (to within 0.03 Å) guanidyl portion of the organic ligand exists in different tautomeric forms in the two complexes: N$_3$ is protonated in 4 while N$_5$ is protonated in 5. As a result,

(17) X-band EPR at 90 K in frozen aqueous (pH 5.8) solutions. 4: $g_{\parallel} =$ 2.332, $g_{\perp} = 2.078$, $|A_{\parallel}(\text{Cu})| = 0.0147$ cm^{-1}. 5: $g_{\parallel} = 2.199$, $g_{\perp} = 2.052$, $|A_{\parallel}(\text{Cu})| = 0.0191$ cm^{-1}, $|A_{\perp}(\text{N})| = 0.0016$ cm^{-1}.
(18) Billo, E. J. Inorg. Nucl. Chem. Lett. 1974, 10, 613.

the gaunidyl double bond is between C$_7$ and N$_5$ in 4 and between C$_7$ and N$_3$ in 5. Bond lengths and angles of interest in 4 include Cu–N$_1$, 1.972 (4) Å; Cu–N$_6$, 2.036 (5) Å; Cu–S, 2.700 (1) Å; C$_7$–N$_3$, 1.333 (7) Å; C$_7$–N$_4$, 1.321 (8) Å; C$_7$–N$_5$, 1.351 (7) Å; C$_8$–N$_6$, 1.159 (7) Å; S–Cu–N$_1$, 78.8 (1)°; S–Cu–N$_6$, 93.2 (1)°; N$_1$–Cu–N$_6$, 91.7 (2)°; C$_7$–N$_5$–C$_8$, 119.2 (5)°; N$_5$–C$_8$–N$_6$, 172.5 (6)°. Bond lengths and angles of interest in 5 include Cu–N$_1$, 1.962 (5) Å; Cu–N$_3$, 1.954 (5) Å; Cu–N$_6$, 1.944 (6) Å; Cu–S, 2.353 (2) Å; Cu–O$_{11}$, 2.505 (6) Å; Cu–O$_{12}$, 2.805 (7) Å; C$_7$–N$_3$, 1.289 (8) Å; C$_7$–N$_4$, 1.344 (9) Å; C$_7$–N$_5$, 1.384 (8) Å; C$_8$–N$_6$, 1.255 (9) Å; C$_8$–O, 1.325 (7) Å; C$_{11}$–O, 1.456 (8) Å; N$_5$–C$_8$–N$_6$, 124.0 (5)°; N$_5$–C$_8$–O, 107.6 (5)°; C$_8$–O–C$_{11}$, 119.4 (5)°; O$_{11}$–Cu–O$_{12}$, 174.1 (2)°; S–Cu–N$_6$, 176.7 (2)°; N$_1$–Cu–N$_3$, 163.2 (2)°; bond angles subtended at Cu by atoms occupying cis octahedral coordination sites range from 78.1 to 99.5°.

The mechanism by which metal-assisted solvolysis of a nitrile function occurs is not well understood.[19] However, in an effort to determine if this reaction would occur for 1 under simulated physiological conditions, the reactivity of 4 was explored. Addition of 1 equiv of 1 to an aqueous solution of 4 at pH 7.0 at 25 °C caused only a small change in the absorption spectrum of the solution over a period of several days. However, heating the above solution for 4 h at 80 °C resulted in a blue solution which spectroscopically was nearly identical with 5.[20] Purging this solution with H$_2$S to percipitate the Cu(II) as CuS followed by workup yielded an impure oil. ^{13}C NMR spectral data indicate a structure for the oil consistent with the amide 2.[21] This amide is also produced in the absence of metal by mild acid hydrolysis of cimetidine.[2]

Although the conditions necessary for modifying the drug are severe by biological standards and thus are not likely to occur in vivo, the tendency of the drug to bind Cu(II) suggests that metal interactions may be important for the biological activity of cimetidine. Future studies with the drug will concentrate on determining the strength of the metal interactions and on establishing the existence of Cu(II) complexes under physiological conditions.

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(20) A (CH$_3$OH) (ϵ), 310 (3140), 612 (150) nm.
(21) 3: ^{31}C NMR (CD$_3$OD, 20 MHz) proton-coupled spectra δ 10.06 (q, J_{CH} = 130 Hz, 4-CH$_3$), 25.24 (t), 29.62 (q, J_{CH} = 140 Hz, NCH$_3$), 31.70 (t), 42.44 (t), 127.68 (s, Im), 129.05 (s, Im), 134.61 (d, J_{CH} = 220 Hz, C-2, Im), 155.61 (s, CO), 157.45 (s, C=N).
(22) (a) Chemistry Department, University of Nebraska; (b) Crystalytics Company.
(23) Camille and Henry Dreyfus Teacher–Scholar.

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**Coordination Stabilization of Organic Intermediates.
Crystal Structure of
{[(en)$_2$Co(SCH$_2$CH$_2$NH$_2$)]$_2$I}(NO$_3$)$_5$·4H$_2$O, a Stable
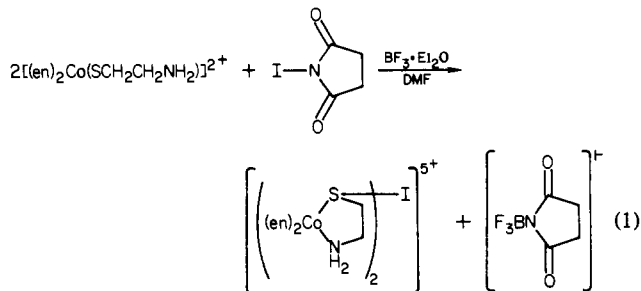Complex of Iodine(I)**

Sir:

Under appropriate conditions the oxidation of thiols coordinated to cobalt(III) leads to stable, S-bonded, coordinated sulfenic acids which may be isolated and characterized.[1] Since noncoordinated
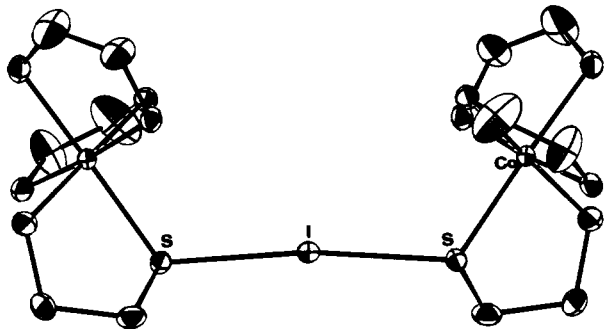
Figure 1. A projection of the $[(en)_2Co(SCH_2CH_2NH_2)]_2I^{5+}$ cation perpendicular to the twofold axis through the iodine atom with 20% probability ellipsoids. Selected bond lengths (Å) are S–I = 2.619 (2), Co–S = 2.244 (3), and average Co–N = 1.98 (2). The S–I–S bond angle is 173.0(1)°.
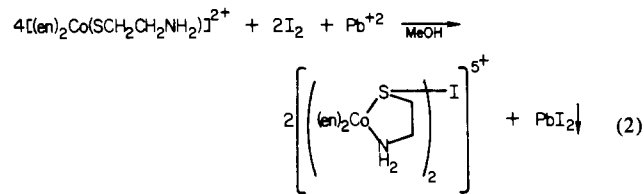
sulfenic acids are very unstable molecules,[2] this coordination-induced stabilization offers the possibility of investigating the chemistry of an otherwise elusive species.[1a,b] In order to determine if other reactive molecules postulated to be of importance in organic and biological sulfur chemistry can also be stabilized by coordination to a robust metal center, we have attempted the syntheses of coordinated sulfenyl iodides (RSI). Noncoordinated sulfenyl iodides are very reactive species that are thought to be important intermediates in many organic[3-5] and bioorganic systems including thyroid iodination reactions,[6-8] coupling of ATP synthesis to thiol oxidation,[9] and the iodine labeling of organic and biomolecules by using enzymes such as lactoperoxidase.[10]

We have found that I^+-donating reagents such as N-iodosuccinimide,[11] iodine nitrate,[12] and molecular iodine react with the prototype thiolato complex $[(en)_2Co(SCH_2CH_2NH_2)]^{2+}$ to yield the remarkably stable adduct $\{[(en)_2Co(SCH_2CH_2NH_2)]_2I\}^{5+}$. The structure of this adduct is shown in Figure 1. Equations 1 and 2 describe two of the preparative reactions.


The $\{[(en)_2Co(SCH_2CH_2NH_2)]_2I\}^{5+}$ adduct may be viewed as

a derivative of a coordinated sulfenyl iodide or as a stabilized derivative of the iodine(I) ion, I^+; this latter view reflects the structural similarities between $\{[(en)_2Co(SCH_2CH_2NH_2)]_2I\}^{5+}$ and the bis(thiourea)iodine(I) adduct,[13] $\{[(NH_2)_2C=S]_2I\}^+$, which is the only other structurally characterized compound in which a formally I^+ center bridges two sulfur atoms. The $\{[(en)_2Co(SCH_2CH_2NH_2)]_2I\}^{5+}$ adduct mimics organic sulfenyl iodides in its reactions with thiols[5] to form disulfides (eq 3). This reaction

$$R = C(CH_3)_3, CH_2CH_2NH_3^+$$
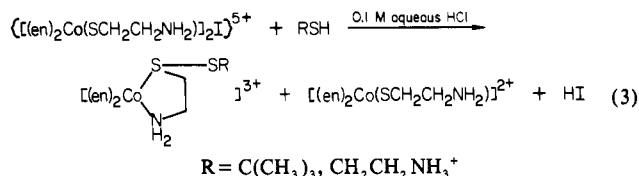
provides a convenient alternative to the route presented earlier[14] for the synthesis of coordinated disulfides.

In addition to the X-ray structural analysis described below, $\{[(en)_2Co(SCH_2CH_2NH_2)]_2I\}^{5+}$ has been characterized by elemental analyses of isolated salts,[15] by its elution characteristics on Sephadex SP C-25 cation-exchange resin which are consistent with a formal charge of >4+ in aqueous solution, and by its visible–UV absorption spectrum[16] which indicates that the coordinated thiolato chromophore of the parent complex has been significantly altered.[1b,14,17] While $\{[(en)_2Co(SCH_2CH_2NH_2)]_2I\}^{5+}$ exhibits remarkable stability relative to noncoordinated sulfenyl iodides, it does suffer slow decomposition in both the solid state and in aqueous solution; this decomposition yields, among other products, molecular iodine and $[(en)_2Co(SCH_2CH_2NH_2)]^{2+}$.

An attempt to grow crystals of the mixed nitrate perchlorate salt from an aqueous (pH 1) medium led to single crystals of red $\{[(en)_2Co(SCH_2CH_2NH_2)]_2I\}(NO_3)_5\cdot 4H_2O$. These crystals belong to the space group $C2/c$, $Z = 4$, with $a = 15.217$ (3), $b = 8.909$ (4), $c = 27.504$ (7) Å, and $\beta = 100.82$ (2)°, $d_{calcd} = 1.85$ g cm^{-3}, $d_{obsd} = 1.91$ (3) g cm^{-3}. The structure was solved by standard Patterson and Fourier methods using 2650 independent reflections ($I > 2\sigma(I)$, $2.5° < 2\theta < 46°$, Mo Kα radiation). Final least-squares refinement of 241 parameters (overall scale factor, positional and anisotropic temperature parameters for nonhydrogen atoms) converged to a conventional R factor of 0.069. The structure (Figure 1) shows each cobalt center to be approximately

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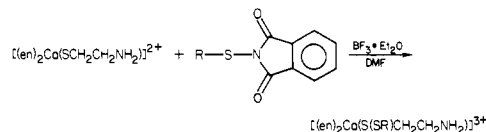
(15) Anal. Calcd for $([(en)_2Co(SCH_2CH_2NH_2)]_2I)(CF_3SO_3)_5$: Co, 8.5; C, 14.8; H, 3.2; N, 10.1; S, 16.3; I, 8.7; F, 20.6. Found: Co, 8.4; C, 14.4; H, 3.6; N, 9.9; S, 14.65, 15.40; I, 9.2; F, 19.5. Percent S determination is suspect due to difficulties in analyzing for sulfur in the presence of iodine. Calcd for $([(en)_2Co(SCH_2CH_2NH_2)]_2I)(NO_3)_3(ClO_4)_2$: Co, 11.52; S, 6.28; I, 12.43; Cl, 6.95. Found: Co, 11.16; S, 6.00; I, 13.12; Cl, 8.61, 8.03.

(16) $\lambda_{max} = 502$ and 281 nm ($\epsilon = 838$ and 31 400 M^{-1} cm^{-1}, respectively). The spectrum was obtained in 1 M aqueous HCl and extinction coefficients are given per mole of dinuclear adduct. Extinction coefficients are only approximate since the adduct suffers slow decomposition in aqueous media.

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octahedrally coordinated to five nitrogen atoms and a sulfur atom. The iodine atom, which lies on a twofold axis, bridges the two crystallographically related cobalt centers by means of a S–I–S linkage. The presence of five nitrate anions (three of which are disordered) confirms the +1 oxidation state assignment for the iodine atom. The S–I bond length of 2.619 (2) Å is in good agreement with the 2.629 (1) Å reported for $\{[(NH_2)_2C=S]_2I\}^+$.[13] The S–I–S linkage is nearly linear (bond angle of 173(1)°), as is the analogous S–Ag–S linkage in $\{[(en)_2Co(SCH_2COO)]_2Ag\}^{3+}$ (169.4(1)°).[18] The S–I–S angle in the bis(thiourea) adduct is required to be 180.0° by symmetry. A linear S–I–S array is expected for a five-electron pair, trigonal-bipyramidal, I$^+$ center in which the two sulfur atoms occupy axial positions and three lone electron pairs occupy equatorial positions.

The chemistry of $\{[(en)_2Co(SCH_2CH_2NH_2)]_2I\}^{5+}$ as both a prototype coordinated sulfenyl iodide and as a potential aqueous I$^+$ donor is under active investigation.[19]

Supplementary Material Available: Tables of atomic positional and thermal parameters and figure containing all atom labels (3 pages). Ordering information is given on any current masthead page.

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(19) A more complete report of this work will be published later in this journal by the same authors.
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Further Verification of Fluorescence-Detected Circular Dichroism

Sir:

Fluorescence-detected circular dichroism (FDCD) measures the difference in fluorescence intensity excited by left and right circularly polarized light (LCPL and RCPL) and is potentially a powerful probe of conformational changes in macromolecules.[1-4] However, two recent communications have raised questions concerning the interpretation of FDCD in this latter application.[5,6] Moreover, experiments designed to test FDCD theory have been limited by artifacts.[7] We report here experiments in which FDCD gives quantitatively predicted spectra under conditions similar to those encountered with macromolecules. The results indicate that artifacts can be abolished, and theories useful for interpretation of transmission circular dichroism (CD) spectra will also be useful for FDCD.

The first potential problem with FDCD measurements on macromolecules was pointed out by Ehrenberg and Steinberg.[5]

They noted that the fluorescence will be polarized, and therefore photoselection effects must be considered. A detailed theory for this case has been derived.[8] One result is that for an excitation beam propagating in the $\hat{k}$ direction, with a photomultiplier oriented perpendicular to this along the $\hat{j}$ axis, with a polarizer in front of it, the measured signal, S_F, is[7,8]

$$S_F = \frac{K(F_L - F_R)}{F_L + F_R} =$$
$$-14.32 \left[\frac{8R(1 + \cos^2 \phi) + (8R_{33}/3)(2 - 3 \cos^2 \phi)}{D(4 - \cos^2 \phi) - (D_{33}/3)(2 - 3 \cos^2 \phi)} - 2R_l \right] \tag{1}$$

K is an instrument constant, F_L and F_R are fluorescence intensities measured for left and right circularly polarized excitation, ϕ is the angle the polarizer axis makes with the $\hat{i}$ axis (orthogonal to $\hat{j}$ and $\hat{k}$), R and D are the average rotational and dipole strengths, respectively, and R_{33} and D_{33} are, respectively, the rotational strength along and dipole strength polarized in the direction of the emission transition moment. R_l is given by

$$R_l = \frac{\Delta A}{2A} - \frac{2.303\Delta A \times 10^{-A}}{2(1 - 10^{-A})} \tag{2}$$

where A is the absorbance of the sample and ΔA is the absorbance for LCPL minus that for RCPL. In eq 1, if $\phi = 35.25°$, the terms in R_{33} and D_{33} vanish. Further, if only one absorbing species is present, eq 1 can be used to predict the FDCD spectrum since $4R/D$ and R_l can be obtained from transmission CD and absorption spectra.[3] Experiments on d-10-camphorsulfonic acid in glycerol are in agreement with the theory, but additional verification has been prevented by large artifacts.[7] These are due to imperfect CPL. For example, suppose the excitation beam contains residual linear polarization at an angle, α, to the $\hat{i}$ axis (in the $\hat{i}\hat{j}$ plane); then the fluorescence signal due to this excitation when $\phi = 0°$, $F_j(\phi = 0)$, is given by

$$F_j(\phi = 0) = F_{\parallel} \cos^2 \alpha + F_{\perp} \sin^2 \alpha \tag{3}$$

Here $F_{\parallel}$ and $F_{\perp}$ are the intensities of fluorescence polarized parallel and perpendicular to the excitation light, respectively. If α is different for left and right circularly polarized cycles, then a difference in fluorescence is measured that does not depend on the sample optical activity. In practice, this artifact can swamp the optical activity signal.[7] A similar artifact has plagued measurements of Raman optical activity but has recently been overcome by Hug.[9,10] We have modified Hug's detection scheme for FDCD. In the new detection system, a second photomultiplier is placed perpendicular to the first (i.e., along the $\hat{i}$ axis). The equivalent of eq 3 for this phototube is

$$F_i(\phi = 0) = F_{\parallel} \sin^2 \alpha + F_{\perp} \cos^2 \alpha \tag{4}$$

Summing the outputs of the two phototubes gives a signal independent of α, since $\sin^2 \alpha + \cos^2 \alpha = 1$. This eliminates the artifact caused only by linear polarization.[11] However, an additional artifact remains that we preliminarily attribute to finite divergence of the excitation beam. One manifestation of this artifact is that spectra with $\phi = 45°$ are not the same as spectra with no polarizer. This last artifact is removed by averaging spectra of $\pm\phi$.

The effectiveness of the two-photomultiplier system is demonstrated by the spectra of morphine in 90% glycerol shown in Figure 1. The depolarization ratio for this sample is 0.3 in the long-wavelength band,[12] and large artifacts can be observed.

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