New Amine Trithiolate Tripod Ligand and Its Iron(II) and Iron(III) Complexes

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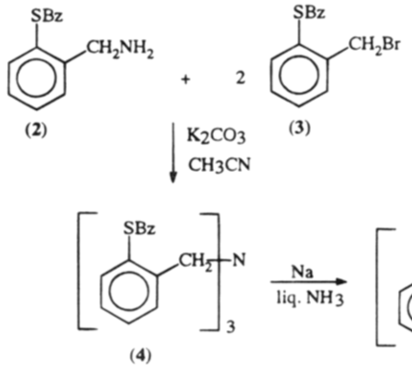
Cysteine coordination is a significant feature in numerous metalloproteins and enzymes.[1] It has been possible to reproduce many of the structural and electronic aspects of these metal centers in synthetic analogs by using simple thiolate ligands. However, attempts to reproduce the reactivity of metal cysteine metalloenzymes have necessitated the creation of new polydentate ligand systems.[2−4] We report the synthesis of a new amine trithiolate tripod ligand, tris(2-mercaptobenzyl)amine, and its novel coordination chemistry with Fe(II) and Fe(III). Tripod ligands, which played an important historic role in the chemistry of the transition metals,[5,6] have been receiving much renewed attention.[6−11]

Scheme 1



The synthetic route to tris(2-mercaptobenzyl)amine (**1**) is shown in Scheme 1. In step 1 the thiol-protected benzylamine (**2**) is reacted with 2 equiv of the corresponding benzyl bromide (**3**) in CH_3CN with K_2CO_3 to give the tertiary amine (**4**) in 80% yield.[12] Removal of the thiol-protecting groups by reaction with Na in liquid ammonia gives the ligand (**1**), which is isolated as the hydrochloride salt in 40% yield.[13]

The reaction of the deprotonated ligand, $[N(CH_2\text{-}o\text{-}C_6H_4\text{-}SLi)_3]$, with $FeCl_2$ in EtOH followed by the addition of Ph_4PBr gives a brown crystalline solid, which can be recrystallized from hot CH_3CN. Characterization of the product, $[Ph_4P][Fe^{II}(N(CH_2\text{-}o\text{-}C_6H_4S)_3)]$ (**5**), by X-ray crystallography (Figure 1)[14] shows the $[Fe^{II}(NS_3)]^-$ core to have a distorted tetrahedral geometry. The Fe atom is 0.37 Å below the plane of the three S donor atoms with an Fe−N distance of 2.127(5) Å. The average Fe−S distance (2.314(13) Å) is 0.06 Å shorter than the Fe−S distance in $[Fe(SPh)_4]^{2-}$.[15] This difference is consistent with the change from the MS_4 to the MS_3N coordination mode.[16] The overall structure of the $[Fe^{II}(N(CH_2\text{-}o\text{-}C_6H_4S)_3)]^-$ anion has idealized C_3 symmetry and is therefore chiral. This chirality is reflected in the diastereotopic nature of the benzyl protons. The ^1H NMR spectrum of **5** (CD_2Cl_2) shows six shifted resonances of equal intensity; the four resonances at δ 29.0, 16.5, −21.0, and −24.5 are assigned to the phenyl protons, and the two resonances at δ 151.0 and 137.0 are assigned to the benzyl protons. The large difference in the chemical shifts of the benzyl protons reflects the two Fe−N−C−H dihedral angles (176° and 57°).[17] Compound **5** provides an unusual example of a tetradentate ligand that supports tetrahedral coordination. The cyclic voltammogram of **5** shows a quasi-reversible Fe^{3+}/Fe^{2+} redox couple at −0.13 V (DMF; versus SCE). In comparison, the redox couple for $[Fe(SPh)_4]^{2-/-}$ occurs at −0.50 V.[18]

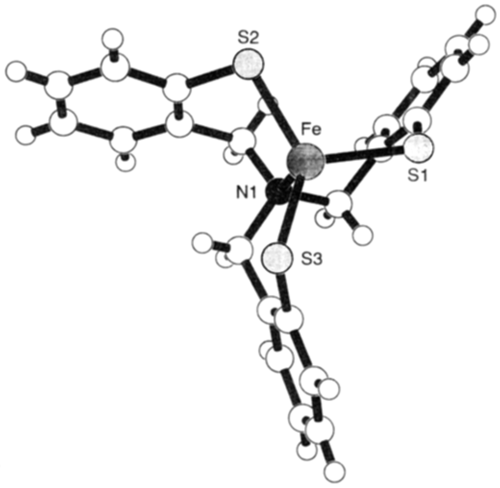


Figure 1. Structural diagram of the anion $[Fe^{II}(N(CH_2\text{-}o\text{-}C_6H_4S)_3)]^-$ (**5**). Selected bond distances (Å) and angles (deg): Fe1−S1 2.304(2), Fe1−S2 2.309(2), Fe1−S3 2.323(2), Fe1−N1 2.127(5), S1−Fe1−S2 112.81(9), S1−Fe1−S3 113.77(8), S1−Fe1−N1 100.3(1), S2−Fe1−S3 125.99(9), S2−Fe1−N1 98.9(1), S3−Fe1−N1 98.3(1), Fe1−S1−C7 100.1(2), Fe1−S2−C14 100.3(2), Fe1−S3−C21 104.1(3).

Air oxidation of $[Fe^{II}(N(CH_2\text{-}o\text{-}C_6H_4S)_3)]^-$ **5** in the presence of 1-methylimidazole gives an intense blue-red solution from which the neutral compound $[Fe^{III}(N(CH_2\text{-}o\text{-}C_6H_4S)_3)(1\text{-}Me\text{-}$

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(1) Lippard, S. J.; Berg, J. M. *Principles of Bioinorganic Chemistry*; University Science Books: Mill Valley, CA, 1994.

(2) Holm, R. H.; Ciurli, S.; Weigel, J. A. *Prog. Inorg. Chem.* **1990**, *38*, 1.

(3) Sellman, D.; Mahr, G.; Knoch, F. *Inorg. Chim. Acta* 1994, 224, 35 and previous papers.

(4) Beissel, T.; Bürger, K. S.; Voight, G.; Wieghardt, K. *Inorg. Chem.* **1993**, *32*, 124.

(5) Sacconi, L.; Mani, F. *Transition Met. Chem. (N.Y.)* **1982**, *8*, 179 and references therein.

(6) Meali, C.; Ghilardi, C. A.; Orlandini, A. *Coord. Chem. Rev.* **1992**, *120*, 361−387.

(7) de Vries, N.; Cook, J.; Jones, A. G.; Davison, A. *Inorg. Chem.* **1991**, *30*, 2662.

(8) Franolic, J. D.; Wang, W. Y.; Millar, M. *J. Am. Chem. Soc.* **1992**, *114*, 6588. Franolic, J. D.; Millar, M.; Koch, S. A. *Inorg. Chem.* **1995**, *34*, 1981.

(9) Freundlich, J. S.; Schrock, R. S.; Cummins, C. C.; Davis, W. E. *J. Am. Chem. Soc.* **1994**, *116*, 6476 and references therein.

(10) Verkade, J. G. *Acc. Chem. Res.* **1993**, *26*, 483.

(11) Spies, H.; Glaser, M.; Pietzsch, H.-J.; Hahn, F. E.; Kintzel, O.; Lügger, T. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1354.

(12) ^1H NMR (δ $CDCl_3$) of **4**: 3.54 (s, 2H, CH_2−N), 3.97 (s, 2H, CH_2−S), 6.9-7.7 ppm (m, 9H, Ar).

(13) ^1H NMR (δ DMSO-d_6) of **1**: 3.64 (s, 6H, CH_2), 7.14 (m, 6H, Ar), 7.31 (d, 3H, Ar), 7.39 ppm (d, 3H, Ar).

(14) $[Ph_4P][Fe(N(CH_2\text{-}o\text{-}C_6H_4S)_3)]$ (**5**), $FeS_3PNC_{45}H_{38}$, crystallizes in the monoclinic space group $P2_1/c$ with $a = 11.099(2)$ Å, $b = 25.715(2)$ Å, $c = 14.030(2)$ Å, $\beta = 107.55(6)°$, $V = 3817(2)$ Å^3, $Z = 4$. Final least squares refinement using 2542 unique reflections with $I > 3\sigma(I)$ gave R (R_w) = 0.044 (0.044).

(15) Coucouvanis, D.; Swenson, D.; Baenziger, N. C.; Murphy, C.; Holah, D. G.; Sfarnas, N.; Simopoulos, A.; Kostikas, A. *J. Am. Chem. Soc.* **1981**, *103*, 3350−3362. Silver, A.; Koch, S. A.; Millar, M. *Inorg. Chim. Acta* **1993**, *205*, 9.

(16) Gruff, E. S.; Koch, S. A. *J. Am. Chem. Soc.* **1989**, *111*, 8762. Corwin, D. T., Jr.; Koch, S. A. *Inorg. Chem.* **1988**, *27*, 493.

(17) The benzyl protons in the ^1H NMR spectrum of the Cd analog of **5** are separated by 1.2 ppm.

(18) Maelia, L. E.; Millar, M.; Koch, S. A. *Inorg. Chem.* **1992**, *31*, 4594.

0002-7863/95/1517-8468$09.00/0

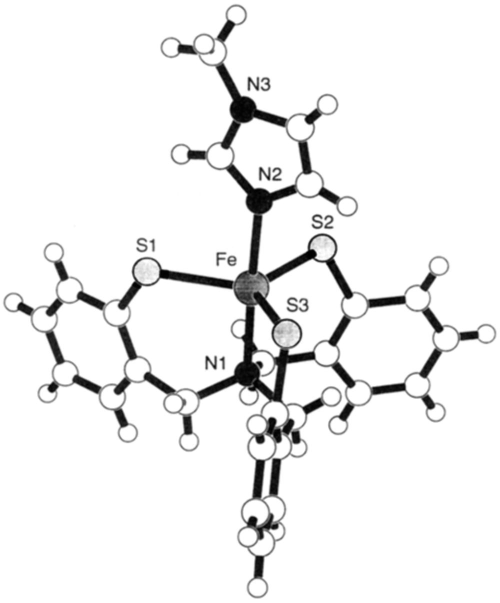

Figure 2. Structural diagram of [$Fe^{III}(N(CH_2$-*o*-$C_6H_4S)_3)$(1-Me-imid)] (**6**). Selected bond distances (Å) and angles (deg): Fe1−S1 2.308(4), Fe1−S2 2.304(5), Fe1−S3 2.296(5), Fe1−N1 2.21(1), Fe1−N2 2.15(1), S1−Fe1−N1 93.7(3), S1−Fe1−N2 88.1(3), S2−Fe1−S3 117.6(2), S2−Fe1−N1 93.0(3), S2−Fe1−N2 83.6(3), S3−Fe1−N1 94.2(3), S3−Fe1−N2 87.5(3), N1−Fe1−N2−176.7(5), Fe1−S1−C7 110.6(5), Fe1−S2−C14 109.4(6), Fe1−S3−C21 111.3(5).

imid)] (**6**) crystallizes.[19] Alternatively, the reaction of **1** with [Et_4N][Fe^{III}(O-2,6-$Me_2C_6H_3)_4$] and 1-methylimidazole in CH_3CN also gives **6** via a ligand exchange reaction in 55% yield.[18] The results of the X-ray crystal structure analysis are shown in Figure 2.[20] Imidazole adds as an axial ligand opposite the amine nitrogen to give a trigonal bipyramidal geometry (N2−Fe−N1 = 176.7(5)°). The coordination of the imidazole results in the movement of the Fe atom into the plane of the three sulfur atoms. The distance from Fe to the amine nitrogen increases by 0.08 Å to 2.21(1) Å. The Fe−S bonds remain virtually unchanged at 2.302(6) Å despite the increase in the oxidation state; but Fe−S−C angles increase from 101(2)° in **5** to 110(1)° in **6**. The [$N(CH_2$-*o*-$C_6H_4S)_3$] ligand maintains its chiral C_3 conformation. The room temperature magnetic moment of **6** is consistent with a high spin, $S = {}^5/_2$ ground state.[21] The electronic spectrum of **6** shows a strong low-energy absorption band at 607 nm.[19] Fe(III) centers with mixed cysteine and histidine coordination have been indicated in the enzyme nitrile hydratase,[22] in metal center II in the protein desulfoferrodoxin,[23] and in the blue non-heme iron protein, neelaredoxin.[24] All these proteins show a strong absorption in the range 600−710 nm. The Fe(III) complex of a hexadentate triamine trithiolate ligand also shows an absorbance in this region.[4]

The monomeric nature of **5** and **6** is a very attractive feature of these compounds. The coordination chemistry of thiolate ligands often results in metal dimers and oligomers with thiolate bridges.[25] The stability of the [$M(N(CH_2$-*o*-$C_6H_4S)_3)$] unit and its ability to add ligands to its vacant coordination site suggest that this metal ligand system should yield significant new chemistry. The structural changes in **5** and **6** find analogy with the structural changes between five-coordinate and six-coordinate iron heme compounds. In this analogy, the N_4 plane of the heme is replaced by the S_3 plane of the NS3 ligand. Trigonal FeS_3 coordination units are also of interest since the structure of the iron−molybdenum cofactor of nitrogenase indicates the existence of tricoordinate FeS_3 sites.[26] Further chemistry of this ligand system with a variety of transition metals is under investigation.

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Supporting Information Available: Tables of crystallographic parameters, atomic coordinates, thermal parameters, and bond distances and angles for **5** and **6** (20 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

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(19) Electronic spectrum of **6** in DMF λ_{nm} (e_M): 355 nm (5910 M^{-1} cm^{-1}), 387 sh (5360), 514 (4440), 607 (4392).

(20) [$Fe^{III}(N(CH_2$-*o*-$C_6H_4S)_3)$(1-Me-imid)] (**6**) $FeS_3N_3C_{25}H_{24}$, crystallizes in the monoclinic space group $P2_1/a$ with $a = 14.800(3)$ Å, $b = 10.804(2)$ Å, $c = 15.128(2)$ Å, $\beta = 94.80(2)°$, $V = 2410(1)$ Å^3, $Z = 4$. Final least squares refinement using 1105 unique reflections with $I > 3\sigma(I)$ gave R (R_w) = 0.056 (0.048).

(21) Koch, S.; Holm, R. H.; Frankel, R. B. *J. Am. Chem. Soc.* **1975**, *97*, 6714.

(22) Jin, H.; Turner, I. M.; Nelson, M. J.; Grubiel, R. J.; Doan, P. E.; Hoffman, B. *J. Am. Chem. Soc.* **1993**, *115*, 5290.

(23) Tavares, P.; Ravi, N.; Moura, J. J. G.; LeGall, J.; Huang, Y.-H.; Crouse, B. R.; Johnson, M. K.; Huynh, B. H.; Moura, I. *J. Biol. Chem.* **1994**, *269*, 10504.

(24) Chen, L.; Sharma, P.; Le Gall, Marino, A. M.; Teixeira, M.; Xavier, A. V. *Eur. J. Biochem.* **1994**, *226*, 613.

(25) Dance, I. G. *Polyhedron* **1986**, *5*, 1037.

(26) Chan, M. K.; Kim, J.; Rees, D. C. *Science* **1993**, *260*, 792.