Pyrazolyl[(methylthio)methyl]borates: hybrid ligands providing nitrogen and sulfur donors

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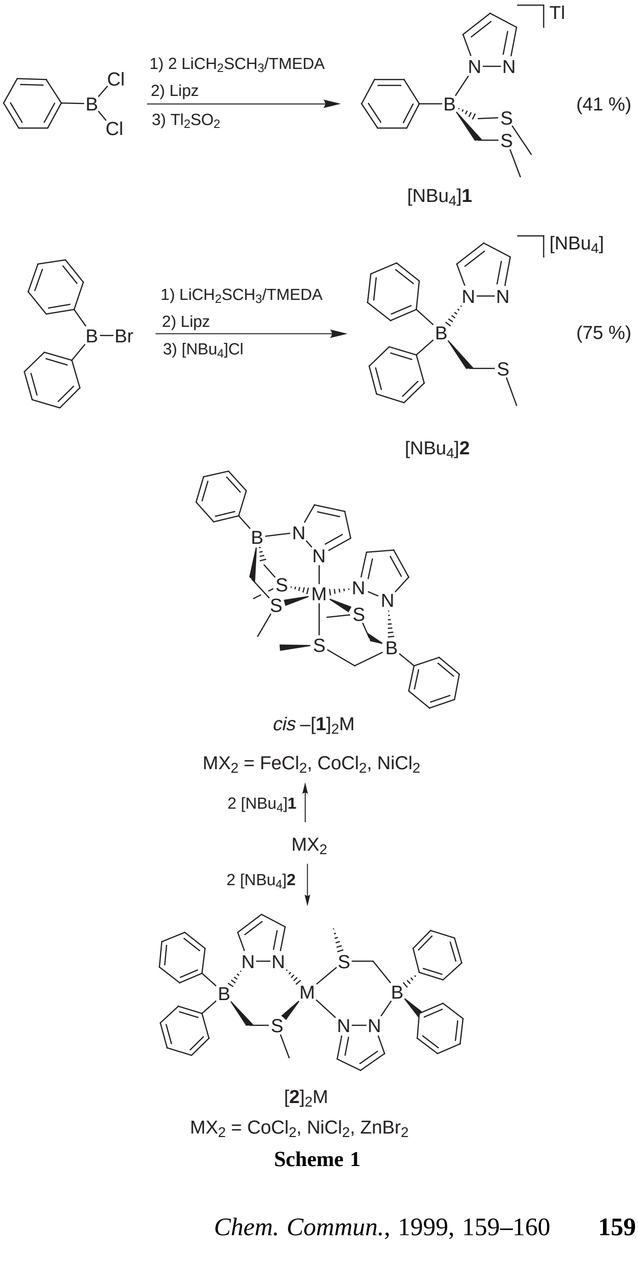
Two new borate ligands, $PhB(CH_2SCH_3)_2(pz)^-$ (1^-) and $Ph_2B(CH_2SCH_3)(pz)^-$ (2^-) (pz = 1-pyrazolyl), have been prepared to provide mixed donor sets, ‘NS_2’ and ‘NS’, respectively, to transition metal ions.

Metalloenzyme catalytic sites often contain coordination spheres that consist of a mixture of nitrogen and sulfur ligands in the forms of histidine, cysteine and methionine residues. Representative examples include the zinc sites in liver alcohol dehydrogenase[1] and methionine synthase,[2] the nickel sites in carbon monoxide dehydrogenase/acetyl coenzyme A synthase[3] and cobalt- and iron-containing nitrile hydratases.[4] A fundamental understanding of the chemical transformations performed by these enzymes would be advanced by the preparation of synthetic representations of these sites. To this end, we have designed and prepared a new series of borate ligands that contain nitrogen and sulfur donors. This first report highlights the preparation, and spectroscopic and structural characterization of representative metal ion derivatives of a tridentate ‘NS_2’ ligand (1^-) and a bidentate ‘NS’ ligand (2^-). Face-capping ‘N_xS_y’ chelate complexes derived from borates have been reported recently by Parkin and co-workers.[5] However, our contribution combines the synthetic flexibility of pyrazolyls and thioethers into a versatile ligand class wherein steric and electronic properties may be intimately tuned by judicious choice of substituents at the 3-pyrazolyl position *and* on sulfur.[6,7] While the ligands may be viewed as hybrids of Trofimenko’s hydridotris(pyrazolyl)borates, Tp^-,[8] and our phenyltris((alkylthio)methyl)borates, $PhTt^-$,[9] we find that the metal complexes possess properties not predicted from such a simplified extrapolation.

The synthesis of ligands 1^- and 2^- proceeded smoothly using the one-pot, stepwise protocol outlined in Scheme 1. Using the appropriate borane, the thioether substituent(s) was/were added first followed by the pyrazolyl group. The ligands were isolated cleanly by precipitation from water as either the Tl^+ or N^+Bu_4 salts in moderate to good yield. The metal complexes were prepared *via* metathesis from the appropriate metal halide (Scheme 1). For example, synthesis of *cis*–[**1**]$_2$Ni proceeds in 60% yield from the reaction of 2 equiv. of [NBu$_4$]**1** and $NiCl_2\cdot6H_2O$ in methanol. Recrystallization from CH_2Cl_2–Et_2O yielded purple blocks. Analytical and combustion data† were consistent with the indicated formula that was corroborated by X-ray diffraction analysis.‡ The molecular structure of *cis*–[**1**]$_2$Ni is depicted in Fig. 1 with selected metric parameters given in the caption. The coordination geometry is octahedral with four sulfur and two nitrogen donors. The most noteworthy and unexpected feature of the structure is the *cis* configuration. The Ni–N bond lengths of 2.063(2) and 2.053(2) Å are similar to those in the all-nitrogen analogue containing two different Tp^- ligands, $[Tp^{3-iPr,4-Br}][Tp^{3,5-Me2}]Ni$, 2.05–2.16 Å.[10] The four Ni–S distances are all similar averaging to 2.47 Å. This value matches that in the S_6 derivative, $[PhTt]_2Ni$, 2.433 Å.[9] The *trans* influence of pyrazolyl and thioether donors is similar in this case as evidenced by experimentally indistinguishable Ni–S distances for sulfur *trans* to nitrogen *vs*. sulfur *trans* to sulfur. Consistent with little-to-no preference for *cis vs. trans* structures in NiS_4N_2 complexes are the *trans* structures of $[([9]aneS_2N)_2Ni]^{2+}$ and $[([10]aneS_2N)_2Ni]^{2+}$ in which nine- and ten-membered macrocycles, respectively, are the chelating ligands.[11] The macrocycles differ from 1^- in that secondary amines are the nitrogen donors rather than pyrazoles. Analogous derivatives of Fe(II) and Co(II) have been prepared. Spectroscopic data are consistent with exclusive production of *cis*–[**1**]$_2$Fe and *cis*–[**1**]$_2$Co.† *cis*–[**1**]$_2$Fe appears to be a spin-crossover complex with a room temperature magnetic moment of 4.1 μ_B. *cis*–[**1**]$_2$Co is high spin with a magnetic moment of 4.1μ_B, close to the spin-only value. For comparison, in the all sulfur analogs, $[PhTt]_2Fe$ exhibits spin-crossover behavior and $[PhTt]_2Co$ is low-spin.[10] Complete details will be reported elsewhere.[12]



Scheme 1

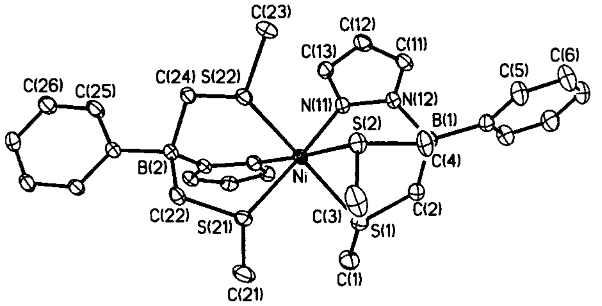


Fig. 1 (a) Thermal ellipsoid plot of *cis*-[**1**]$_2$Ni at 30% probability level showing the atom labeling scheme. The hydrogen atoms are omitted for clarity. Selected bond distances (Å) and bond angles (°): Ni–N(11) 2.053(2), Ni–N(31) 2.067(2), Ni–S(1) 2.4678(8), Ni–S(2) 2.4545(7), Ni–S(21) 2.4859(6), Ni–S(22) 2.4620(7), S(1)–Ni–S(2) 82.92(3), S(1)–Ni–N(11) 92.27(6), S(2)–Ni–N(11) 86.46(6), N(11)–Ni–N(31) 92.99(8), N(11)–Ni–S(21) 176.87(6), S(1)–Ni–S(22) 161.22(3).

Four coordinate complexes [**2**]$_2$M, (M = Ni, Co and Zn), have been prepared in 70–80% yield from the bidentate ligand, **2**$^-$, (Scheme 1).† The molecular structure of pink [**2**]$_2$Co has been determined (Fig. 2).‡ The geometry is tetrahedral with two sulfur and two nitrogen donors. The solution magnetic moment, 4.0 μ_B, is consistent with three unpaired electrons. While this represents the first crystallographically determined structure of Co(II) with two nitrogen and two *thioether* sulfur ligands, there are molecular precedents that contain two nitrogen and two thiolate donors.[13] The ligand bond angle of 100.11(1)° (N–Co–S) is larger than that of the bis[(methylthio)methyl] chelate, Ph$_2$Bt$^-$ [86.31(1)°], reflecting the sp^2 hybridization of the pyrazolyl nitrogens.[14] Each six-membered chelate ring is in the twist-boat conformation. [**2**]$_2$Co and the isostructural Zn complex, [**2**]$_2$Zn, are chiral possessing C_2 point symmetry. Consistent with C_2 symmetry, the ^{1}H NMR spectrum of [**2**]$_2$Zn contains well resolved methylene resonances for the diastereotopic protons.† Although the phenyl substituents on boron are also expected to be magnetically inequivalent, their resonances are not well separated and appear as broad features. [**2**]$_2$Ni is square planar based on its NMR (diamagnetic) and electronic spectra. Interpretation of the proton NMR spectrum of [**2**]$_2$Ni, displaying signals qualitatively analogous to those observed for [**2**]$_2$Zn, specifically diastereotopic methylene and broad aryl resonances, is consistent with a single isomer in solution. To date, crystallographic data collected on [**2**]$_2$Ni has not yielded a chemically reasonable solution. Consequently, the identity of the single isomer, *cis* or *trans*, remains unknown. Given the disposition of ligand substituents in [**1**]$_2$Ni, it is attractive to propose that the single isomer is *cis*-[**2**]$_2$Ni. This geometry provides the favorable electronic configuration of placing the strong σ-donor nitrogen ligands *trans* to the thioethers. Efforts to improve the quality of the crystals for X-ray analysis continue. Additionally, we aim to distinguish the isomeric form of [**2**]$_2$Ni in solution using molecular dipole moment measurements.

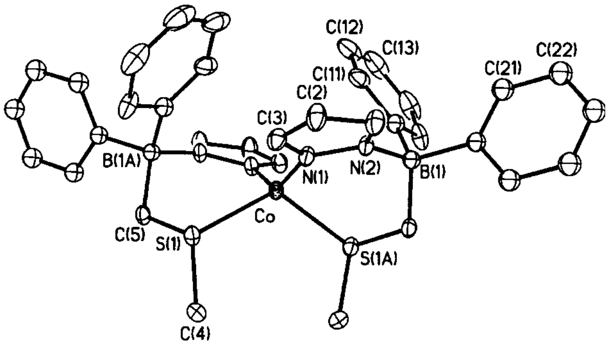


Fig. 2 (a) Thermal ellipsoid plot of [2]2Co•2C$_6$H$_{14}$ at 30% probability level showing the atom labeling scheme. The hydrogen atoms and solvent molecules are omitted for clarity. Selected bond distances (Å) and bond angles (°): Co–S(1) 2.362(1), Co–N(1) 1.957(3), S(1)–Co–N(1) 101.1(1), S(1)–Co–S(1A) 117.67(7), S(1)–Co–N(1A) 100.1(1), S(1A)–Co–N(1) 100.1(1).

Research in progress is directed toward utilizing the new donor sets as supporting ligands for the preparation of synthetic analogues for the zinc sites in methionine synthase, cobalt-containing nitrile hydratase and the nickel sites in CO dehydrogenase.

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Footnotes and references

† Spectroscopic and analytical data for new compounds are consistent with the proposed structures.

‡ *Crystal data* for C$_{26}$H$_{36}$B$_2$N$_4$NiS$_4$ (*cis*-[**1**]$_2$Ni): M = 613.2, triclinic, space group $P\bar{1}$, a = 7.9656(1), b = 12.7601(2), c = 15.6007(2) Å, α = 79.9636(7), β = 82.8552(8), γ = 74.3877(2)°, V = 1498.78(5) Å^3, Z = 2, T = 198(2) K, μ = 0.949 mm^{-1}, $R(F)$ = 0.0416 for 5045 observed independent reflections ($4 \leqslant 2\theta \leqslant 57°$). For C$_{34}H_{34}B_2CoN_4S_2$ ([**2**]$_2$Co)•2C$_6$H$_{14}$: M = 817.7, monoclinic, space group $C2/c$, a = 22.1546(7), b = 10.1634(3), c = 21.7947(6) Å, β = 117.423(1)°, V = 4356.0(3) Å^3, Z = 4, T = 198(2) K, μ = 0.527 mm^{-1}, $R(F)$ = 0.0659 for 2714 observed independent reflections ($4 \leqslant 2\theta \leqslant 57°$). There are two molecules of *n*-hexane co-crystallized in the asymmetric unit. Based on a preliminary structure of minimum quality, [**2**]$_2$Zn is isostructural with [**2**]$_2$Co: monoclinic, space group $P2_1/c$, a = 12.4085(2), b = 36.8532(15), c = 14.5336(6) Å, β = 96.1980(8)°, V = 6607.2(8) Å^3, Z = 8, T = 198(2) K. CCDC 182/1114.

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