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Communication

Pyrazolate-Bridging Dinucleating Ligands Containing Hydrogen-Bond Donors: Synthesis and Structure of Their Cobalt Analogues

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Convergent preparative routes to new urea–pyrazolate dinucleating ligands are described. Metal complexes of these ligands have hydrogen bond donors that are proximal to the metal centers that interact with other coordinated species. This is exemplified by Co^{II} dimers with Co^{II}–μ-Cl–Co^{II} motifs, in which the chloro ligand is involved in four intramolecular hydrogen bonds. These noncovalent interactions appear to influence the Co^{II}–Cl bonds, which are unusually long, having lengths greater than 2.5 Å.

Hydrogen bonds (H-bonds) that are formed within a secondary coordination sphere can effectively control metal-mediated processes.[1,2] This control is typified by their presence at the active sites of metalloproteins, in which H-bonds are proposed to regulate function in a wide variety of heme and non-heme systems, including the decomposition of superoxide in Fe- and Mn-containing superoxide dismutases,[3] dioxygen activation in methane monooxygenase[2] and cytochrome P450,[4] and H-atom abstraction in lipoxygenase.[5] H-bonds in metalloprotein active sites normally form between amino acid residues of the protein backbone and external ligands coordinated to the active-site metal ions. Exploiting such noncovalent intramolecular interactions in synthetic systems would be useful in establishing structure−function relationships that are necessary for the development of new chemical reagents. In the absence of a protein scaffold surrounding a metal ion, synthetic complexes need relatively rigid frameworks containing functional groups in the correct orientations to promote the formation of intramolecular H-bonds. In recent years, reports have appeared about multidentate ligands containing appended H-bond donors/acceptors that are positioned proximal to a coordinatively unsaturated metal center.[6] For instance, our group has prepared a series of urea-based tripodal ligands that form intramolecular H-bonds to coordinated oxo, hydroxo, sulfido, and amido ligands.[7] As with most multidentate ligands of this type, our tripods are designed to support the formation of monomeric complexes.

In this Communication, we describe the development of dinucleating ligands with cavities comprised of four H-bond donors.[8] The design concept is illustrated in Figure 1 and begins with our preexisting tripodal urea compound, H_6**buea**. We have found that the deprotonated α-NH groups of the ureas will bind to a metal ion to form stable, five-membered

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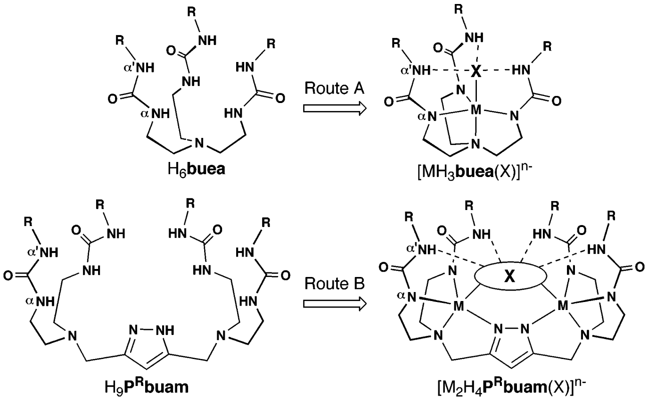
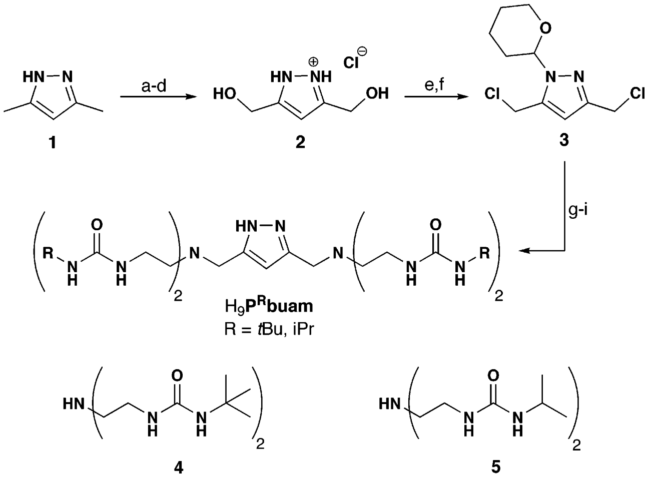


Figure 1. Design idea for H-bond donating ligands.

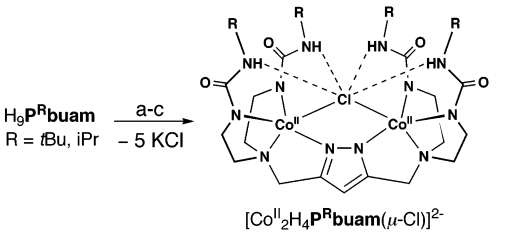
chelate rings that incorporate an apical amine N atom (Route A). The α′-NH group of each urea remains protonated and serves as an H-bond donor to external species (X) that bind within the cavity. The urea groups are sufficiently rigid so as to enforce intramolecular H-bond formation. Coupling two of these tripods together by the removal of one urea arm and replacing them with a 3,5-disubstituted pyrazole unit result in dinucleating ligands 3,5-bis{bis[(*N*′-R-ureayl)-*N*-ethyl]aminomethyl}-1*H*-pyrazole ($H_9\mathbf{P^{R}buam}$) that have cavities composed of four intramolecular H-bond donors (Route B). Our choice of this bridging group was motivated by reports from Okawa et al.[9] and Meyer et al.,[10,11] who showed that metal−metal separations range from 3.4 to 4.5 Å when methylene groups are used as linkers to the pyrazole ring. Thus, we have prepared $H_9\mathbf{P^{R}buam}$ (R = *t*Bu and iPr) and their Co^{II} dimers.

Scheme 1 [a]



[a] Conditions: (a) KMnO$_4$, H$_2$O, Δ, 56%; (b) HCl(g), EtOH, rt, 81%; (c) LiAlH$_4$, ether, Δ, N$_2$; (d) ethanolic HCl, 80%; (e) SOCl$_2$, Δ, 94%; (f) 1,2-dihydropyran, CH$_2$Cl$_2$, rt, 75%; (g) **4** or **5**, Na$_2$CO$_3$, CH$_3$CN, N$_2$, Δ, >81%; (h) ethanolic HCl, rt; (i) Na$_2$CO$_3$(aq), >88%.

Scheme 2 [a]



[a] Conditions: (a) 5 equiv of KH, DMA, rt, Ar; (b) 2 equiv CoCl$_2$, DMA, rt, Ar; (c) 2 equiv [*n*Pr$_4$N]Cl, DMA, rt, Ar.

A convergent procedure was developed to synthesize the $H_9\mathbf{P^{R}buam}$ ligands in multigram quantities (Scheme 1). Preparation of the bridging unit started with 3,5-dimethylpyrazole (**1**), which was converted to the dicarboxylate derivative following the method of Bosnich et al.[12] After esterification and reduction to bis(hydroxymethyl)pyrazole hydrochloride (**2**), the dichloro analogue was isolated and protected as compound **3** using Meyer et al.'s procedure.[13] The bis[(alkylureayl)-*N*-ethyl]amine compounds **4** and **5** were prepared in three steps according to the procedure developed by Lucas.[14] Coupling **3** with the diurea compounds and subsequent deprotection produced $H_9\mathbf{P^{\mathit{t}Bu}buam}$ and $H_9\mathbf{P^{iPr}buam}$ as white solids in overall yields from **1** of 22% and 18%, respectively.[15]

To evaluate the structural properties of metal complexes with $H_9\mathbf{P^{\mathit{t}Bu}buam}$ and $H_9\mathbf{P^{iPr}buam}$, we prepared the corresponding Co^{II} dimers. Outlined in Scheme 2, the procedures were initiated by deprotonation with 5 equiv of KH in *N*,*N*-dimethylacetamide (DMA). After gas evolution ceased, the addition of 2 equiv of CoCl$_2$ resulted in blue-purple solutions. Cation metathesis with [*n*Pr$_4$N]Cl afforded $[n\mathrm{Pr_4N}]_2[\mathrm{Co^{II}_2H_4}\mathbf{P^{R}buam}(\mu\text{-Cl})]$ in yields greater than 60%.[15] X-ray-quality crystals were obtained by vapor diffusion of diethyl ether into DMA solutions of the metal salts, which were stable for weeks under a dry, anaerobic environment.

Single-crystal X-ray diffraction measurements corroborate the similarities of the solid-state structures for $[n\mathrm{Pr_4N}]_2[\mathrm{Co^{II}_2H_4}\mathbf{P^{\mathit{t}Bu}buam}(\mu\text{-Cl})]\cdot\mathrm{DMA}$ and $[n\mathrm{Pr_4N}]_2[\mathrm{Co^{II}_2H_4}\mathbf{P^{iPr}buam}(\mu\text{-Cl})]\cdot 0.5\mathrm{DMA}$. The molecular structure of the isopropyl derivative, which is presented in Figure 2, reveals that the Co^{II} centers are five-coordinate with distorted trigonal-bipyramidal geometries. The primary coordination sphere of each Co^{II} ion contains two urea−α-N^{-} atoms, one pyrazolate N atom, and a bridging Cl^{-} ion with an average Co^{II}−Cl bond length of 2.6279(4) Å for $[\mathrm{Co^{II}_2H_4}\mathbf{P^{iPr}buam}(\mu\text{-Cl})]^{2-}$ and 2.570(1) Å for $[\mathrm{Co^{II}_2H_4}\mathbf{P^{\mathit{t}Bu}buam}(\mu\text{-Cl})]^{2-}$. The *t*Bu analogue has identical Co^{II}−Cl bonds, whereas $[\mathrm{Co^{II}_2H_4}\mathbf{P^{iPr}buam}(\mu\text{-Cl})]^{2-}$ exhibits a small, but statistically significant, deviation from a symmetrical Co^{II}−Cl−Co^{II} unit, with

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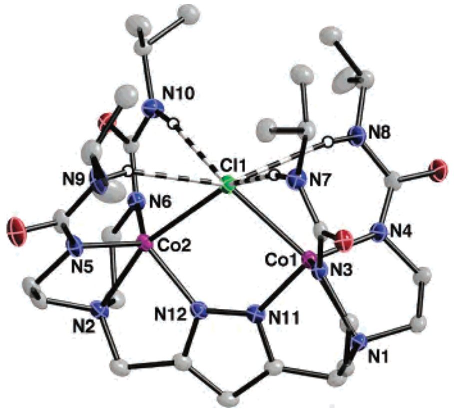

Figure 2. Thermal ellipsoid diagram of $[\mathrm{Co^{II}_2H_4}\mathbf{P^{iPr}buam}(\mu\text{-Cl})]^{2-}$. The ellipsoids are drawn at the 50% probability level, and only the urea H-atoms are shown for clarity. Selected bond lengths (Å) and angles (deg): Co1−Cl1 2.5974(4), Co1−N1 2.2147(11), Co1−N3 2.0075(11), Co1−N4 1.9935(11), Co1−N11 2.0217(11), Co2−Cl1 2.6584(4), Co2−N2 2.1998(12), Co2−N5 1.9920(12), Co2−N6 2.0092(11), Co2−N12 2.0170(11), Co1···Co2 4.1132(3), N7···Cl1 3.368(1), N8···Cl1 3.364(1), N9···Cl1 3.386(1), N10···Cl1 3.347(1); N3−Co1−N4 115.48(5), N3−Co1−N11 118.06(5), N4−Co1−N11 117.55(5), N3−Co1−Cl1 104.28(3), N4−Co1−Cl1 109.77(3), N11−Co1−Cl1 85.81(3), N3−Co1−N1 81.92(4), N4−Co1−N1 81.13(4), N11−Co1−N1 76.96(4), N1−Co1−Cl1 162.56(3), N5−Co2−N6 115.37(5), N5−Co2−N12 116.06(5), N6−Co2−N12 120.37(5), N5−Co2−Cl1 110.90(4), N6−Co2−Cl1 103.30(3), N12−Co2−Cl1 84.60(3), N5−Co2−N2 81.83(5), N6−Co2−N2 81.37(4), N12−Co2−N2 78.06(4), N2−Co2−Cl1 161.89(3), Co1−Cl1−Co2 102.995(12).

differences in the $\mathrm{Co^{II}}$−Cl bond lengths of 0.06 Å. The $\mathrm{Co^{II}}$−Cl bond lengths in both complexes are approximately 0.2 Å longer than is typical for the $\mathrm{Co^{II}}$−μ-Cl−$\mathrm{Co^{II}}$ motif, which usually have $\mathrm{Co^{II}}$−Cl lengths of less than 2.42 Å.[16]

These unusually long $\mathrm{Co^{II}}$−Cl bonds are caused in part by the intramolecular H-bonding network surrounding the bridging $\mathrm{Cl^-}$ ion. The observation of average α′-N···Cl distances of 3.366(1) Å for $[\mathrm{Co^{II}_2H_4}\mathbf{P^{iPr}buam}(\mu\text{-Cl})]^{2-}$ and 3.349(4) Å for $[\mathrm{Co^{II}_2H_4}\mathbf{P^{\mathit{t}Bu}buam}(\mu\text{-Cl})]^{2-}$, along with N−H···Cl angles greater than 140°, is consistent with intramolecular H-bond assignment;[17] however, the H-bonding networks are different for the two complexes. In the iPr analogue, all of the α′-N···Cl distances are statistically equal, which produces a symmetrical H-bond network around the chloro ligand. In contrast, $[\mathrm{Co^{II}_2H_4}\mathbf{P^{\mathit{t}Bu}buam}(\mu\text{-Cl})]^{2-}$ possesses two "diagonal" pairs of H-bonds. One pair has an average α′-N···Cl distance of 3.397(4) Å and involves the H-bond donors from N8 and N9. The other H-bonding pair utilizes donors containing N7 and N10 and has a shorter average α′-N···Cl distance of 3.301(4) Å. The Fourier transform IR spectra for both complexes support this observation by displaying a single sharp peak for the N−H vibrations in the iPr analogue, while multiple bands are observed for the *t*Bu analogue (Figures S3 and S4 in the Supporting Information). This difference between H-bond networks is attributed to steric effects of the R groups attached to the α′-NH groups. The bulkier *t*Bu groups in $[\mathrm{Co^{II}_2H_4}\mathbf{P^{\mathit{t}Bu}buam}(\mu\text{-Cl})]^{2-}$ are oriented so that the methyl groups are within the cavity, nearly eclipsing the urea H-atoms and thereby preventing a symmetrical distribution of H-bonds (Figure S1 in the Supporting Information). In $[\mathrm{Co^{II}_2H_4}\mathbf{P^{iPr}buam}(\mu\text{-Cl})]^{2-}$, the methyl groups are also within the cavity but generally directed away from the α′-N−H vectors. This difference can be seen in the complexes' dihedral $\mathrm{C_{methyl}}$−$\mathrm{C_{methine}}$−α′-N−H angles:[18] for $[\mathrm{Co^{II}_2H_4}\mathbf{P^{\mathit{t}Bu}buam}(\mu\text{-Cl})]^{2-}$, it spans the range 1.55−10.31°, while for $[\mathrm{Co^{II}_2H_4}\mathbf{P^{iPr}buam}(\mu\text{-Cl})]^{2-}$, the range is between 16.58 and 107.31°. Note that the methine protons of the iPr groups in $[\mathrm{Co^{II}_2H_4}\mathbf{P^{iPr}buam}(\mu\text{-Cl})]^{2-}$ are oriented outside the cavity, away from the $\mathrm{Co^{II}}$−μ-Cl−$\mathrm{Co^{II}}$ core (Figure 2).

Perpendicular- and parallel-mode X-band electron paramagnetic resonance (EPR) spectra were recorded on both complexes in the solid state at low temperatures. The complexes show perpendicular-mode EPR signals with g values near 4 and 2. These g values are indicative of mononuclear $S = {}^3/_2$ $\mathrm{Co^{II}}$ species. Spin quantification of the signals indicated that these species represented less than 5% of the Co in the samples. Parallel-mode EPR spectra show a weak signal near $g = 8$, which increases in intensity at $T = 15$ K. A ferromagnetic spin exchange between two $S = {}^3/_2$ $\mathrm{Co^{II}}$ ions would produce a ground-state spin system of $S = 3$. We tentatively assign the $g = 8$ signal to an excited doublet within either an $S = 2$ or 3 manifold of a ferromagnetic exchange interaction between the two $\mathrm{Co^{II}}$ ions. An antiferromagnetic exchange interaction would produce a diamagnetic ground state, with the $S = 2$ and 3 spin manifolds high in energy, which would not be expected to show a signal at 2 K. Further work is required to determine the spin-state assignment and magnitude of the exchange interaction. Similar results were observed for the complexes in DMA, suggesting that the complexes are stable in solution. Previous reports of metal dimers with ligands related to $[\mathrm{H_4}\mathbf{P^{R}buam}]^{5-}$ found some evidence for an exchange interaction between metal centers.[10,19]

In summary, we have developed new dinucleating ligands that provide H-bond networks proximal to the coordinated metal centers. Structural studies on $\mathrm{Co^{II}}$−μ-Cl−$\mathrm{Co^{II}}$ complexes illustrate the effects of intramolecular H-bonds: the unusually long $\mathrm{Co^{II}}$−Cl distances are caused in part by the H-bond network surrounding the $\mathrm{Cl^-}$ ion. The R groups appended from the urea groups also appear to affect the H-bond interactions, suggesting that additional control of the secondary sphere may be possible. Efforts to elucidate these effects are ongoing.

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Supporting Information Available: Details for all experiments, spectra, and crystallographic details for $[n\mathrm{Pr_4N}]_2[\mathrm{Co^{II}_2H_4}\mathbf{P^{\mathit{t}Bu}buam}(\mu\text{-Cl})]\cdot\mathrm{DMA}$ and $[n\mathrm{Pr_4N}]_2[\mathrm{Co^{II}_2H_4}\mathbf{P^{iPr}buam}(\mu\text{-Cl})]\cdot0.5\mathrm{DMA}$ (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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