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Carboxylate-Bridged Heterodimetallic Complexes

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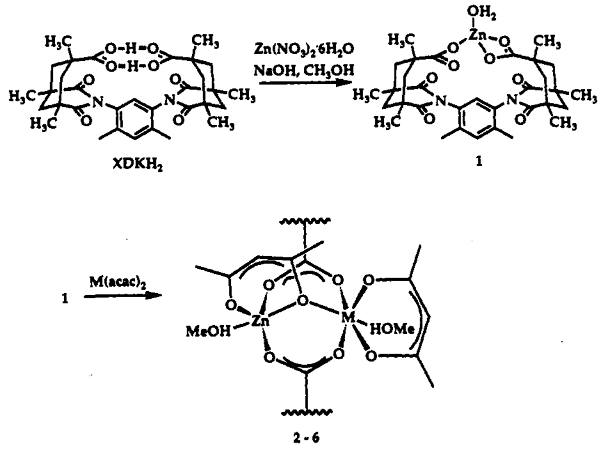
Carboxylate-bridged dimetallic centers comprise a rapidly expanding class of metalloenzyme active sites. Included are several heterodimetallic centers such as the FeZn core in kidney bean purple acid phosphatase,[1] a CoZn or MgZn center in bovine lens aminopeptidase,[2,3] and a MnCa unit in concanavalin A.[4] Despite their biological importance, our understanding of the chemistry of these carboxylate-bridged heterodimetallic centers is limited, owing in part to the lack of good synthetic routes to and the small number of structurally characterized examples of, appropriate model compounds. Two notable prior achievements are (i) $[MM'(\mu\text{-}O)(\mu\text{-}CH_3CO_2)_2(Me_3TACN)_2]^{n+}$and $[MM'(\mu\text{-}OH)(\mu\text{-}CH_3CO_2)_2(Me_3TACN)_2]^{n+}$ complexes, where M, M′ is a first row transition metal ion or Ru and Me_3TACN is 1,4,7-trimethyl-1,4,7-triazacyclononane,[5] and (ii) $[FeM(BPMP)(\mu\text{-}carboxylate)_2]^{n+}$ complexes, where M is Mn, Cu, or Zn and HBPMP is 2,6-bis[(bis(2-pyridylmethyl)amino)methyl]-4-methylphenol.[6] Here, we wish to report a new general route to heterodimetallic complexes bridged by the dinucleating carboxylate ligand XDK, where H_2XDK is *m*-xylenediamine bis(Kemp's triacid imide) (Scheme 1).[7] This ligand, previously used in the preparation of stable dinuclear Fe(II), Fe(III), and Co(II) complexes,[8,9] forms a mononuclear Zn(II) derivative that can be cleanly converted into heterodimetallic complexes with a variety of transition metal ions.

Scheme 1



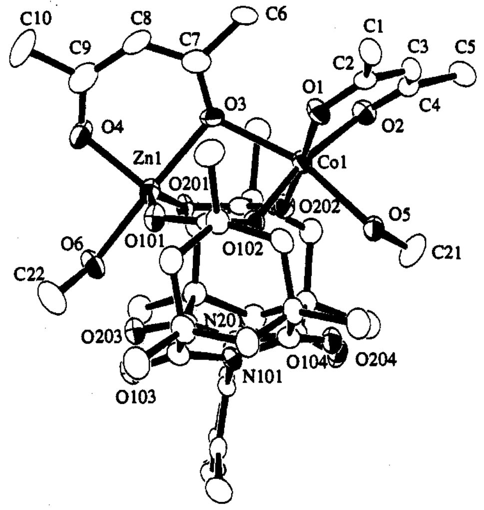


Figure 1. ORTEP view of $[ZnCo(XDK)(acac)_2(CH_3OH)_2]$ (**2**), with hydrogen atoms omitted for clarity. Thermal ellipsoids are drawn at the 50% probability level. Selected bond distances (Å) and angles (deg): Zn(1)···Co(1), 3.440(2); Zn(1)–O(3), 2.135(4); Zn(1)–O(4), 1.964(5); Zn(1)–O(6), 2.107(4); Zn(1)–O(101), 1.967(5); Zn(1)–O(201), 1.964(4); Co(1)–O(1), 2.014(4); Co(1)–O(2), 2.027(5); Co(1)–O(3), 2.224(5); Co(1)–O(5), 2.190(4); Co(1)–O(102), 2.059(4); Co(1)–O(202), 2.051(4); O(3)–Zn(1)–O(4), 90.6(2); O(3)–Zn(1)–O(6), 168.7(2); O(101)–Zn(1)–O(201), 142.0(2); O(1)–Co(1)–O(2), 88.6(2); O(3)–Co(1)–O(5), 163.2(2); O(102)–Co(1)–O(202), 94.5(2).

The reaction of $Zn(NO_3)_2\cdot 6H_2O$ with Na_2XDK in methanol gave the colorless mononuclear complex $[Zn(XDK)(H_2O)]$ (**1**).[10] Treatment of **1** with an additional equivalent of $M(acac)_2\cdot nH_2O$ (acac = 2,4-pentanedionate) in refluxing methanol for 30 min afforded the series of dimetallic complexes, $[ZnM(XDK)(acac)_2(CH_3OH)_2]\cdot H_2O$ (**2**·H_2O, M = Co; **3**·H_2O, M = Mn; **4**·H_2O, M = Fe; **5**·H_2O, M = Ni; **6**·H_2O, M = Zn) in 30–65% yields (Scheme 1).[10] As illustrated for the CoZn derivative in Figure 1, the structures comprise a heterodimetallic center bridged by XDK through its two carboxylate groups and further asymmetrically bridged by the O(3) atom of the acac ligand.[10] The trigonal bipyramidal zinc atom is coordinated by two carboxylate oxygen atoms, two oxygen atoms of the bridging acac ligand, and the hydroxyl oxygen atom of methanol. The heterometal atom adopts a distorted octahedral geometry and is ligated by two carboxylate oxygen atoms, the two oxygen atoms of the chelating acac, the bridging oxygen atom of acac, and the hydroxyl oxygen atom of methanol. The metal–metal separations vary slightly (**3**, Zn···Mn = 3.517(1) Å; **4**, Zn···Fe = 3.492(1) Å; **2**, Zn···Co = 3.440(2) Å; **6**, Zn···Zn = 3.463(1) Å) according to the high-spin octahedral ionic radii of M.[11] The Zn···Fe separation in **4** is shorter than that found in the phosphate-occupied active site of kidney bean phosphatase (3.65 Å determined by EXAFS).[12] The homodinuclear zinc complex **6** may be compared with those in phospholipase C from *Bacillus cereus*[13] and P1 nuclease from

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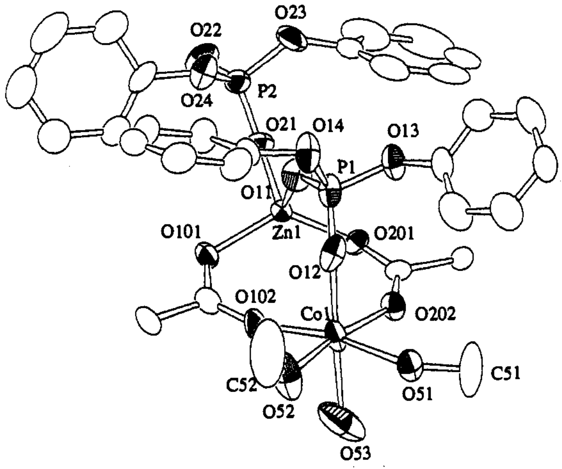

Figure 2. ORTEP view of $[ZnCo(\mu\text{-}\eta^2\text{-}(PhO)_2PO_2)(\eta^1\text{-}(PhO)_2PO_2)(CH_3OH)_2(H_2O)]\cdot CH_3OH$ ($7\cdot CH_3OH$). For clarity, hydrogen atoms and all atoms of the XDK ligand, except for carboxylate oxygen and carbon atoms and α-carbon atoms, have been omitted. Selected bond distances (Å) and angles (deg): Zn(1)···Co(1), 3.846(1); Zn(1)–O(11), 1.930(4); Zn(1)–O(21), 1.936(4); Zn(1)–O(101), 1.947(4); Zn(1)–O(201), 1.926(4); Co(1)–O(12), 2.095(5); Co(1)–O(51), 2.130(4); Co(1)–O(52), 2.098(5); Co(1)–O(53), 2.195(7); Co(1)–O(102), 2.086(4); Co(1)–O(202), 2.070(4); O(11)–Zn(1)–O(21), 102.8(2); O(11)–Zn(1)–O(101), 106.2(2); O(11)–Zn(1)–O(201), 106.3(2); O(21)–Zn(1)–O(101), 103.6(2); O(21)–Zn(1)–O(201), 108.9(2); O(101)–Zn(1)–O(201), 126.6(2); O(12)–Co(1)–O(53), 177.6(2); O(12)–Co(1)–O(102), 96.2(2); O(12)–Co(1)–O(202), 93.5(2); O(102)–Co(1)–O(202), 99.2(2).

Penicillium citrinum, in which two zinc atoms are bridged by an aspartate residue at a 3.2–3.3 Å separation.[2a,14]

The acac ligands of $[ZnM(XDK)(acac)_2(CH_3OH)_2]$ can readily be replaced by phosphate esters. For example, reaction of **2** with 2 equiv of diphenylphosphoric acid in 1:1 CH_3OH/CH_2Cl_2 solution afforded the novel bis(phosphate ester)-substituted complex $[ZnCo(XDK)(\mu\text{-}\eta^2\text{-}(PhO)_2PO_2)(\eta^1\text{-}(PhO)_2PO_2)(CH_3OH)_2(H_2O)]$ (**7**). The structure of $7\cdot CH_3OH$, determined by X-ray crystallography (Figure 2),[10] contains a ZnCo center bridged by XDK through its two carboxylate groups and by a diphenyl phosphate ligand. A second diphenyl phosphate ligand is terminally coordinated to the zinc atom in a monodentate fashion. Dinuclear complexes with terminally coordinated phosphate ester ligands are rare, a structurally characterized iron example being $[Fe_2Cl_2(\eta^1\text{-}(PhO)_2PO_2)(TBPO)(CH_3OH)]^{2+}$ (HTBPO = *N,N,N′,N′*-tetrakis(2-benzimidazolylmethyl)-2-hydroxy-1,3-diaminopropane).[15] The Zn···Co distance of 3.846(1) Å in **7** is larger by 0.406 Å than that in **2** and is slightly longer than that in $[Zn^{II}Fe^{III}(BPMP)(\eta^2\text{-}(PhO)_2PO_2)_2](ClO_4)_2$ (3.695(1) Å).[12a] The zinc atom is tetrahedrally coordinated by the two carboxylate oxygen atoms of XDK, the oxygen atom of the bridging phosphate, and O(21) of the monodentate phosphate ligand. The cobalt atom adopts a slightly distorted octahedral geometry ligated by the two carboxylate oxygen atoms of XDK, the oxygen atom of the bridging phosphate, two methanol molecules, and one water molecule.

In summary, the present results reveal that XDK stabilizes carboxylate-bridged heterodimetallics, which may serve as useful models for metalloenzymes that promote hydrolysis of phosphate esters and peptides. The functionally relevant chemistry of these and related complexes is under investigation. The utility of XDK for assembling heterodimetallic complexes has been further demonstrated by reaction of the mononuclear Co(II) complex, [Co(XDK)(neocuproine)], where neocuproine is 2,9-dimethylphenanthroline, with alkali metal salts (MX) to afford heterodimetallic complexes of the general formula [CoM(XDK)(neocuproine)(X)] in good yield. Details of this chemistry will be published separately.[16]

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Supplementary Material Available: Experimental details on the preparation and characterization of **1–7**, tabulations of crystallographic data for **2**, **3**, **4**, **6**, and **7**, positional and anisotropic thermal parameters for **2**, **3**, **4**, **6**, and **7** (18 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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