The first two aqua-bridged dimagnesium(II) complexes: structural models for active sites in dimetallic hydrolases

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Two novel complexes $Mg_2(\mu\text{-}H_2O)(\mu\text{-}OAc)_2(L)_4(OAc)_2$ (L = imidazole or benzimidazole) have been synthesized and characterized; they contain the first example of an aqua-bridged dimagnesium core, and may have implications for the hydrolytic activity of dimetallic hydrolases.

Closely assembled magnesium ions have been found at the active sites of several important hydrolase enzymes.[1] These include inositol polyphosphate 1-phosphatase,[2] inositol mono-phosphatase,[3] *Escherichia coli* DNA polymerase I,[4] rat DNA polymerase,[5] enolase[6] and possibly phosphodiesterase. Although the carboxylate-bridged dimetallic unit has been the subject of extensive studies in mimetic bioinorganic chemistry, the dinuclear magnesium(II) model complex with carboxylate bridges has been very rarely reported. Lippard and co-workers have reported the first dinuclear Mg^{II} model complex with two carboxylate and one phosphodiester bridge.[7] To the best of our knowledge, no dinuclear Mg^{II} complexes with aqua and carboxylate bridges have been reported to date. Our goal has been to synthesize dimetallic model complexes with aqua and carboxylate bridges employing monodentate N-donor ligands such as imidazole (Him), benzimidazole (Bzim) or their analogues which are good mimics of histidine side chains. These ligands not only co-ordinate the metal as N-donors but also provide non-co-ordinating NH groups which form hydrogen bonds with neighboring molecules. Such H bonding has been proposed to play a crucial role in the structural assembly and/or function of many biological systems.[8] In this communication, we report the syntheses and structural characterization of two novel dinuclear Mg^{II} complexes with a (μ-aqua)bis(μ-carboxylate) core, $Mg_2(\mu\text{-}H_2O)(\mu\text{-}OAc)_2(L)_4(OAc)_2$ (L = Him **1** or Bzim **2**), which are the first examples of dinuclear Mg^{II} complexes connected by aqua and carboxylate bridges.

The complexes **1** and **2** were synthesized by reaction of Him or Bzim with $Mg(OAc)_2\cdot4H_2O$ in 2.0 : 1 ratio, respectively, in methanol at room temperature.‡ Colorless single crystals suitable for X-ray crystallographic determination were obtained by diffusing diethyl ether into the methanol solution. The molecular structures of **1** and **2** were determined by X-ray crystallo-

graphic diffraction.§ A dimagnesium(II) core was identified for each complex which is joined by an aqua and two carboxylate bridges. Each of the Mg ions is further co-ordinated by one additional monodentate carboxylate and two N-donor ligands, forming two equivalent but slightly distorted MgN_2O_4 octahedra joined at their shared vertex by the oxygen atom of the bridging water molecule in a face-to-face fashion (Fig. 1). The molecule lies on a crystallographically-imposed two-fold axis passing through the bridging aqua oxygen O(1). The hydrogen atoms of the μ-H_2O were revealed at the highest residual electron density peaks after all other atoms, including the non-water hydrogens, and were included in the crystal structure elucidation. The bridging water ligands were also identified on the basis of the Mg–O (aqua) distances in **1** [2.144(4) Å] and in **2** [2.131(2) Å] which are longer than those in $[Mg(H_2O)_6\text{-}(1\text{-Mecyt})_6]^{2+}$ (average 2.061 Å),[10a] $[Mg(H_2O)_4(1\text{-Mecyt})_2]^{2+}$ (average 2.086 Å) (1-Mecyt = 1-methylcytosine),[10a] $[Mg(H_2O)_4\text{-}(cyt)_2]^{2+}$ (average 2.080 Å) (cyt = cytosine),[10a] $[Mg(OH_2)_6]^{2+}$ (average 2.058 Å),[10b] $[Mg(AMPH)_2(OH_2)_2]$ (2.092 Å) [AMPH = aminomethyl(hydrogen)phosphonate],[10c] $[Mg(L\text{-Asp})(OH_2)_2]$ (average 2.082 Å)[10d] and $[Mg(L\text{-Glu})(OH_2)_4]$ (average 2.076 Å),[10e] respectively, and considerably longer than the distance of Mg–OH (average 1.953 Å) in a $Mg_2(\mu\text{-}OH)_2$ core.[10f] The Mg···Mg distances in **1** [3.656(2) Å] and **2** [3.625(2) Å] are shorter than those found in enolase (4.2 Å),[6] $[Mg_2(XDK)\text{-}(DPP)_2(CH_3OH)_3(H_2O)]$ [4.108(3) Å] [XDK = *m*-xylenediaminebis(Kemp's triacid imide); DPP = diphenylphosphate][7] and rat DNA polymerase (4 Å),[5] and comparable to those found in *E. coli* DNA polymerase I (3.9 Å),[4] inositol polyphosphate 1-phosphatase (3.88 Å),[2] inositol monophosphatase (3.8 Å)[3] and fructose 1,6-bis(phosphatase) (3.7 Å).[11]

Acetate ligands display two co-ordination modes in both complexes, terminal monodentate and bridging bidentate, respectively. Several quite interesting structural features are noticeable in **1** and **2**. First and most important, the terminal carboxylate groups display an interesting geometry. While the distances of C–O (free) [1.251(7) Å] and C–O (co-ordinating) [1.255(7) Å] in **1** are comparable statistically, their counterparts in **2** [1.273(4) for C–O (free) and 1.252(4) Å for C–O (co-ordinating)] are significantly different. Both observations are contrary to the classical geometry of terminally bound monodentate carboxylate groups, in which the distance of C–O (free) is usually significantly shorter than that of C–O (co-ordinating).[12] A careful examination of the structures led us to believe that the elongated C–O (free) distance is the con-
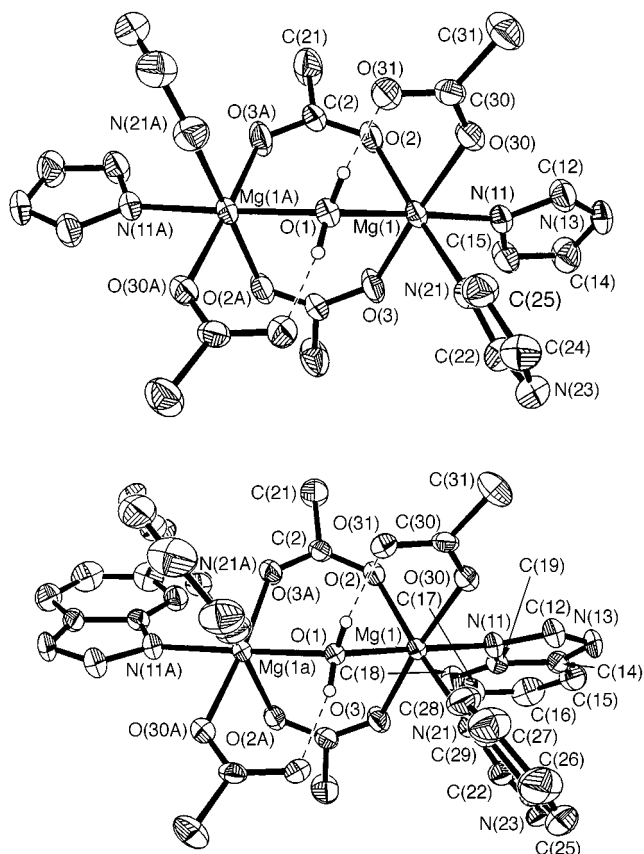
Fig. 1 An ORTEP drawing of complexes **1** (top) and **2** (bottom), showing 40% probability thermal ellipsoids with the atom-labeling scheme. Important interatomic distances (Å) and angles (°) of **1** and **2** (in square brackets): Mg···Mg 3.656(2) [3.625(2)], O(1)···O(31) 2.648(6) [2.621(4)], O(31)···N(23B) 2.763(6) [2.738(5)], O(2)···N(13C) 2.834(6) [2.836(5)], Mg–O(1) 2.144(4) [2.131(2)], Mg–O(2) 2.098(4) [2.080(3)], Mg–O(3) 2.017(4) [2.026(2)], Mg–O(30) 2.072(4) [2.084(3)], Mg–N(11) 2.176(5) [2.187(3)], Mg–N(21) 2.204(5) [2.227(3)], C(30)–O(30) 1.255(7) [1.252(4)], C(30)–O(31) 1.251(7) [1.273(4)], Mg(1)–O(1)–Mg(1A) 117.0(3) [116.5(2)]

sequence of a strong 'pulling effect' on the O (free) atom by two H-bonds, an intramolecular one with the bridging H$_2$O [O(1)···O(31) distances in **1**, 2.648(6) and **2**, 2.621(4) Å] and an intermolecular one with the non-co-ordinating NH group from the adjacent molecule [O(31)···N(23B) in **1**, 2.763(6) and in **2**, 2.738(5) Å], giving rise to what can be regarded as a 'pseudo-bridging' six-membered ring arrangement in the terminal carboxylate groups. The second interesting observation is that the bidentate acetate bridges are markedly asymmetric [Mg–O(2) 2.098(4) and 2.080(3) Å, Mg–O(3) 2.017(4) and 2.026(2) Å for **1** and **2**, respectively], although the molecule as a whole possesses a two-fold symmetry. This can be attributed in part to an additional intermolecular H-bond formed between O(2) and a NH group from an adjacent molecule [O(2)··· N(13C) 2.834(6) in **1** and 2.836(5) Å in **2**]. The significance of the observed framework of H-bonds in the formation and stabilization of **1** and **2** can therefore be envisioned. The water molecule in a bridging fashion between two magnesium centers is stabilized by the intramolecular H-bonds formed with the terminal carboxylates. This H-bond may play a crucial role in the fixation and activation of the bridging H$_2$O in the hydrolysis of the substrate by dimetallic hydrolases.[2–4,6,13]

The IR spectrum of **1** shows that there are two instead of four carboxylate absorption bands at 1624 [$\nu_{as}(CO_2^-)$] and 1423 cm^{-1} [$\nu_s(CO_2^-)$], respectively, reflecting the structural similarity between the terminal monodentate and the bridging bidentate carboxylates. A broad band centered at *ca.* 2370 cm^{-1} was observed in the FT-IR spectrum of **1**, and is attributed to the O–H stretching of the bridging water. The unusual low vibrational frequency of the O–H band stretching is consistent with H$_2$O involvement in strong H bonding as revealed also by the crystal structure. Similar phenomena were also observed for water-bridged dicobalt(II) complexes.[14] The solid-state ^{13}C NMR spectrum of **1** exhibits clearly two sets of resonances for the acetate groups, in agreement with their two binding modes, terminal monodentate and bridging bidentate, in the complex. The solid-state ^{15}N NMR spectrum of **1** also displays two resonances for each nitrogen atom of the co-ordinated Him ligands, consistent with the crystal structure that the two Him ligands on a metal ion are chemically non-equivalent, with one *trans* to the bridging OAc ligand and the other *trans* to the bridging H$_2$O, despite the fact that the two MgN$_2$O$_4$ cores in **1** are equivalent to each other by a two-fold axis.

In conclusion, we have reported the syntheses and structural characterization of two novel dimagnesium(II) complexes with (μ-aqua)bis(μ-carboxylate) cores and with monodentate N-donor Him and Bzim ligands. To the best of our knowledge, **1** and **2** represent the first example of dinuclear Mg^{II} complexes with (μ-aqua)bis(μ-carboxylate) bridges. The terminal monodentate carboxylates display an unusual geometry in **1** and **2**, suggesting the possible existence of isomers in the co-ordination chemistry of carboxylate side chains of amino acids. Finally, we believe that the formation of strong H-bonds between the bridging water and the ancillary carboxylate groups in **1** and **2** provides a good mimic for the active sites of dimetallic hydrolases, in which the terminal carboxylate stabilizes and activates the bridging or bound water co-substrate.[2–4,6,13]

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