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Hexanickel Enediolate Cluster Generated in an Acireductone Dioxygenase Model Reaction

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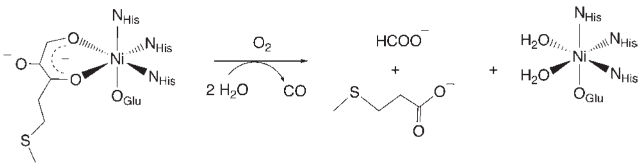
A nickel(II) enediolate cluster (**2**) forms upon treatment of [(6-Ph$_2$-TPA)Ni(PhC(O)C(OH)C(O)Ph)]ClO$_4$ (**1**) with Me$_4$NOH·5H$_2$O in CH$_3$CN. Crystallographic studies of **2** revealed a hexanuclear structure of S_6 symmetry with a formula of {[Ni(PhC(O)C(O)C(O)Ph)(CH$_3$OH)]·1.33CH$_3$OH}$_6$. Because isolation of bulk amounts of **2** from the reaction involving **1** proved impossible, a solvation analogue of **2** (labeled **5**) was generated from admixture of Ni(ClO$_4$)$_2$·6H$_2$O, 2-hydroxy-1,3-diphenylpropane-1,3-dione, and Me$_4$NOH·5H$_2$O in CH$_3$OH/CH$_3$CN. Complex **5** is formulated as {[Ni(PhC(O)C(O)C(O)Ph)(H$_2$O)]·H$_2$O·0.25CH$_3$CN}$_6$ based on elemental analysis, a molecular weight determination, UV−vis, and a magnetic moment measurement. Treatment of **5** with O$_2$ and 6-Ph$_2$TPA (6 equiv) results in the formation of CO and [(6-Ph$_2$TPA)Ni(O$_2$CPh)$_2$(H$_2$O)] (**3**), the latter of which was isolated in 69% yield. The level of ^{18}O incorporation in this reaction matches that for a reaction wherein **2** is generated from **1**. These results provide evidence that a nickel(II) enediolate cluster is the O$_2$ reactive species in a previously reported model reaction for nickel(II)-containing acireductone dioxygenase.

Metal-coordinated enediolate species are proposed to form in the reaction pathways of several enzyme-catalyzed reactions.[1] In nickel(II)-containing acireductone dioxygenase (Ni^{II}ARD), an enediolate form of the substrate is proposed to coordinate to the metal center via a six-membered chelate ring structure (Scheme 1).[2] The reaction of this enzyme/substrate complex with O$_2$ results in aliphatic C−C bond cleavage and the release of CO.

Of relevance to Ni^{II}ARD, we have previously reported that treatment of the mononuclear nickel(II) enolate complex [(6-Ph$_2$TPA)Ni(PhC(O)C(OH)C(O)Ph)]ClO$_4$ (**1**) with Me$_4$NOH·5H$_2$O in CH$_3$CN under anaerobic conditions results in a shift in the absorption maximum of the complex from 399 to ~420 nm (Scheme 2).[3] We proposed that this spectral shift was associated with the formation of a complex (**2**) containing a coordinated enediolate form of the 2-hydroxy-1,3-diphenylpropane-1,3-dione ligand. The addition of O$_2$ to this proposed enediolate species resulted in the formation of CO and a nickel(II) dibenzoate complex, [(6-Ph$_2$TPA)Ni(O$_2$CPh)$_2$(H$_2$O)] (**3**). Because examples of coordination complexes having enediolate ligation of relevance to Ni^{II}ARD are rare, in the research described herein we have further investigated the properties of the proposed enediolate species **2**.

Scheme 1



A reexamination of the reaction mixture produced upon treatment of **1** with Me$_4$NOH·5H$_2$O in CH$_3$CN using thin-layer chromatography revealed the presence of free 6-Ph$_2$-TPA in the solution. This suggested that **2** (λ_{max} = 420 nm) contained some mixture of nickel(II) and the enediolate form of 2-hydroxy-1,3-diphenylpropane-1,3-dione. After exhaustive attempts toward crystallizing this species (**2**), one dark orange-brown platelike crystal suitable for single-crystal X-ray diffraction was obtained from CH$_3$OH/CH$_3$CN/Et$_2$O.[4] The crystal lattice of **2** contains hexanickel clusters packed in layers parallel to the [110] direction. Each hexanickel cluster (Figure 1) is comprised of two layers of Ni^{II} centers, with each layer having three pseudo-octahedral Ni^{II} centers. The deprotonated central oxygen of the enediolate ligand forms the linkage between the layers. Each Ni^{II} is coordinated by five oxygen atoms from the enediolate ligands and is capped with an oxygen atom from a coordinated methanol. The Ni−O distances within each layer are in the

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(4) **2**: C$_{104}$H$_{116}$Ni$_6$O$_{32}$, M = 2230.23, trigonal, $R\overline{3}$, orange-brown plates, a = 17.2952(3) Å, b = 17.2952(3) Å, c = 30.7825(10) Å, V = 7974.2(3) Å^3, Z = 3, T = 150(1) K, 6503 total reflections, 3461 independent reflections {R1 [$I > 2\sigma(I)$] = 0.0501, wR2 (all data) = 0.1241}.

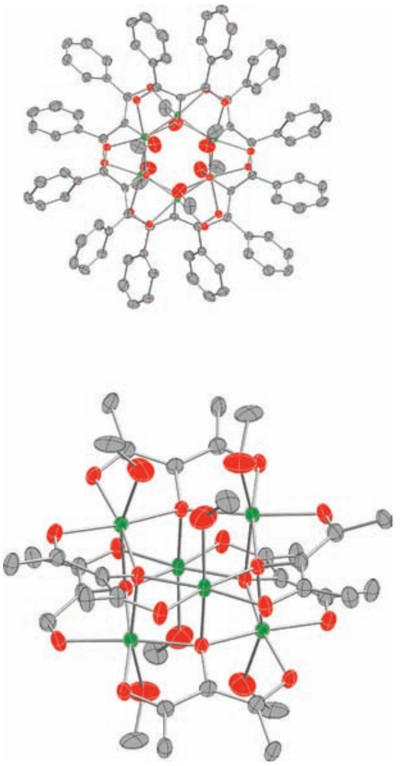
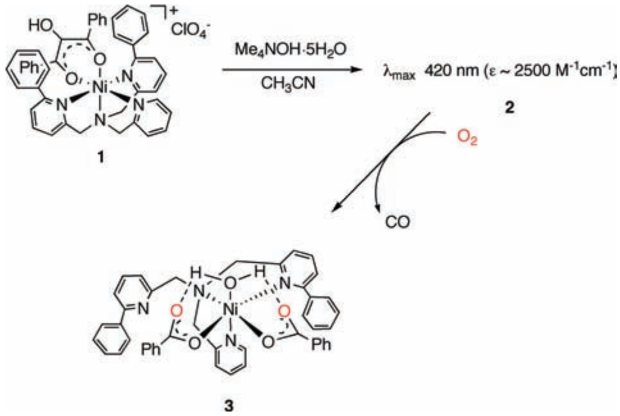


Figure 1. Thermal ellipsoid drawings of the nickel(II) enediolate cluster. Ellipsoids are drawn at the 50% probability level. Color coding for atoms: carbon, gray; oxygen, red; nickel, green. Hydrogen atoms have been omitted for clarity. In the bottom structure, the phenyl appendages have been truncated at the *ipso* carbon to aid visualization of the cluster connectivity.

Scheme 2



range of 2.02–2.05 Å. The Ni–O distance between the layers is 2.133(3) Å. The capping methanol ligand has a Ni–O(methanol) distance of 2.082(3) Å. Positioned between the phenyl appendages of different dianionic 2-hydroxy-1,3-diphenylpropane-1,3-dione ligands within each layer is a molecule of methanol (total of three per layer). An additional one-third occupied methanol molecule per Ni^{II} center is positioned between the clusters in the lattice.

Each layer of **2** (Figure 2a) has some similarity to the Ni_3(enediolate)$_2$ core found in a trinuclear nickel(II) complex **4** (Figure 2b).[5] In both complexes, the enediolate coordinates as a bridging ligand between two Ni^{II} centers. The Ni–O and C–O distances of the enediolate coordination in these complexes are generally similar. However, there are slight differences in the backbone C–C distances [**2**, C(1)–C(2) 1.404(5) Å and C(2)–C(3) 1.403(5) Å; **4**, C(36)–C(37) 1.419(5) Å and C(37)–C(38) 1.387(5) Å]. This could be a consequence of the enediolate bridge being between pseudo-octahedral Ni^{II} centers in **2** and square-planar and pseudo-octahedral Ni^{II} centers in **4**.

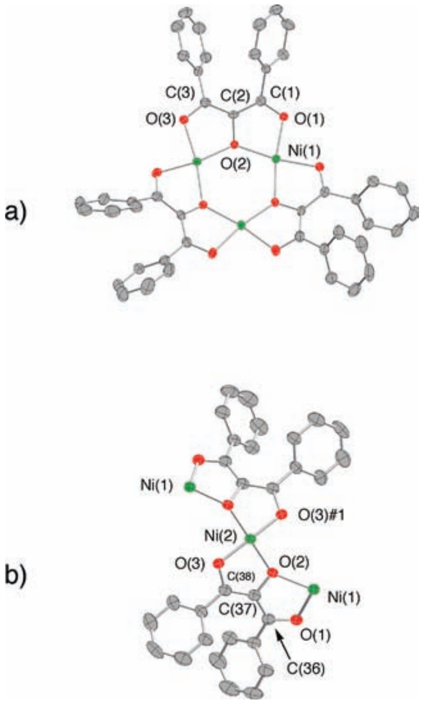


Figure 2. Thermal ellipsoid drawings of one layer of **2** (top) and the core of the trinuclear **4** (bottom). Ellipsoids are drawn at the 50% probability level. Hydrogen atoms and the tetradentate 6-NA-6-Ph_2TPA supporting chelate ligand of the Ni(1) center in **4** have been omitted for clarity. Color coding for atoms: carbon, gray; oxygen, red; nickel, green. Selected bond distances (Å) for **2**: Ni(1)–O(1) 2.023(2), Ni(1)–O(2) 2.041(2), Ni(1)–O(3) 2.045(2), Ni(1)–O(4) 2.082(3) (methanol).

Isolation of a bulk amount of **2** from the reaction mixture proved impossible because of the extreme O_2 sensitivity of this compound and the difficulty of isolating the cluster compound away from the other reaction products (6-Ph_2-TPA and Me_4NClO_4). For this reason, we pursued the independent synthesis of an analogue of **2** via treatment of $Ni(ClO_4)_2{\cdot}6H_2O$ with an equimolar amount of 2-hydroxy-1,3-diphenylpropane-1,3-dione in the presence of 2 equiv of $Me_4NOH{\cdot}5H_2O$ in CH_3CN/CH_3OH. Following workup, an orange-brown precipitate was isolated from CH_2Cl_2/Et_2O and was subsequently dried extensively under vacuum. Elemental analysis of this solid revealed an empirical formula of $[Ni(C_{15}H_{10}O_3){\cdot}2H_2O{\cdot}0.25CH_3CN]$ (**5**). This formulation is very similar to that found per Ni^{II} center in the X-ray structure of **2**, $[Ni(C_{15}H_{10}O_3){\cdot}2.33CH_3OH]$. Specifically, one enediolate and ~2.3 molecules of solvent are present per Ni^{II} center in both **2** and **5**. Unfortunately, efforts to crystallize **5**, even under the same conditions as those used to produce the X-ray crystal of **2**, were unsuccessful. Therefore, to determine whether **5** is a hexanickel cluster, a molecular weight determination in naphthalene was performed using the Rast method and 6-Ph_2TPA as a standard.[6] On the basis of a series

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of measurements (see the Supporting Information), the molecular weight of **5** was determined to be 2100(350) g/mol. Within the limitations of the experiment, this is consistent with the formulation of **5** as a hexanickel cluster. Thus, we propose that both **2** and **5** are hexanickel clusters, albeit they differ in the nature of the solvate molecules that are present. For the magnetic and spectroscopic studies outlined below, on the basis of the elemental analysis data, we have formulated **5** as $\{[Ni(PhC(O)C(O)C(O)Ph)(H_2O)]\cdot H_2O\cdot 0.25CH_3CN\}_6$, which has a molecular weight of 2059 g/mol.

Complex **5** has been characterized by a magnetic moment measurement. With formulation as a hexanickel cluster, a magnetic moment of 8.7(4) μ_B was determined using the Evans method at ambient temperature.[7] Because the magnetic properties of a hexanickel cluster are of current interest,[8] the magnetic properties of **5** remain under investigation.

The UV−vis absorption spectrum of **5** [λ_{max} = 420 nm ($\varepsilon \sim 2400\ M^{-1}\ cm^{-1}$)] is identical with that produced upon treatment of **1** with $Me_4NOH\cdot 5H_2O$ in CH_3CN, which are the conditions under which **2** is generated. This absorption feature is tentatively assigned as a $\pi \rightarrow \pi^*$ transition involving the coordinated enediolate unit. This absorption is red-shifted from that found in **1** (λ_{max} = 399 nm).[9] The FTIR spectrum of **5** [Figure S1(top) in the Supporting Information] has been measured in the solid state (KBr). The vibrations of the enediolate ligand are broadened relative to the vibrations in the starting neutral 2-hydroxy-1,3-diphenylpropane-1,3-dione [Figure S1(bottom) in the Supporting Information]. A broad vibration at ~3420 cm^{-1} in the spectrum of **5** is consistent with the presence of water in the sample. Vibrations in the region of ~1640−1550 cm^{-1} are associated with the enolate C−C and C−O units, as well as aromatic C=C bonds. The ^1H NMR spectrum of **5** was collected under paramagnetic conditions with a spectral window of > 220 ppm.[10] Two broad phenyl proton resonances were identifed in the spectra and located at ~7.8 and 3.1 ppm (Figure S2 in the Supporting Information). Decomposition of **5** upon exposure to O_2 results in only minor changes in the spectrum, primarily in the region of 7−9 ppm. We note that paramagnetic mononuclear nickel(II) benzoate compounds have been previously shown to exhibit aryl ^1H NMR resonances in the 5−11 ppm region.[11] A resonance for H_2O could not be identified in the ^1H NMR spectrum of **5**.

To test the viability of a hexanickel nickel cluster as the O_2 reactive species generated in the reaction of **1** with $Me_4NOH\cdot 5H_2O$ (Scheme 2), we have combined **5** with 6 equiv of 6-Ph_2TPA in CH_3CN and exposed the solution to O_2. This results in the formation of CO and **3** (Scheme 2), the latter of which was isolated in 69% yield from the reaction mixture (see the Supporting Information). This yield matches well with that previously reported (75%) starting from treatment of **1** with $Me_4NOH\cdot 5H_2O$ in CH_3CN followed by exposure to O_2.[3] Performing the reaction involving **5** in the presence of $^{18}O_2$ resulted in a level of isotope incorporation for one oxygen atom of each benzoate ligand (83−86%) that matches with that found starting from **1** (86%).[12] This level of ^{18}O incorporation is the same as that found for the reaction of $[(6\text{-NA-6-}Ph_2TPANi)_2(\mu\text{-}PhC(O)C(O)C(O)Ph)_2Ni](ClO_4)_2$ (**4**). These combined results demonstrate that a similarity in the coordination modes for the enediolate ligand leads to similar levels of ^{18}O incorporation. It should be noted that the reactions involving enediolate complexes (**2**/**5** and **4**) exhibit higher levels of ^{18}O incorporation than is reported for the Ni^{II}ARD enzymatic reaction (77.5%).[13]

In summary, this study has provided evidence that the reactive species in the Ni^{II}ARD model reaction shown in Scheme 2 is a novel hexanuclear nickel(II) enediolate cluster. Because little is currently known about the coordination chemistry of acireductone-type enediolate ligands, this study provides important insight that can be used in the design of new complexes. Specifically, in future efforts toward modeling of the Ni^{II}ARD ES complex, it will be important to employ a supporting chelate ligand that is not easily displaced upon metal enediolate ligation.

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Supporting Information Available: Synthetic and characterization details for **5** including FTIR and ^1H NMR spectra and experimental details of molecular weight determination of **5** and ^{18}O-labeling experiments. This material is available free of charge via the Internet at http://pubs.acs.org.

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(12) We have previously reported that the level of ^{18}O incorporation for the reaction involving **1** in the presence of $Me_4NOH\cdot 5H_2O$ was ~67%. Repeating this experiment under more careful conditions resulted in a higher level (86%) of ^{18}O incorporation.

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