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Ground State Electronic and Magnetic Properties of a μ_3 -Oxo Bridged Trinuclear Cu(II) Complex: Correlation to the Native Intermediate of the Multicopper Oxidases

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Abstract

The ground state electronic and magnetic properties of one of the possible structures of the trinuclear Cu^{II} site in the native intermediate (NI) of the multicopper oxidases, the μ_3 -oxo bridged structure, are evaluated using the C_3 -symmetric Cu_3^{II} complex, $\mu_3\text{O}$. $\mu_3\text{O}$ is unique in that no ligand, other than the oxo, contributes to the exchange coupling. However, $\mu_3\text{O}$ has a ferromagnetic ground state, inconsistent with that of NI. Therefore, two perturbations have been considered: protonation of the μ_3 -oxo ligand and relaxation of the μ_3 -oxo ligand into the Cu_3 plane. Notably, when the oxo-ligand is sufficiently close to the Cu_3 plane ($< 0.3 \text{ \AA}$), the ground state of $\mu_3\text{O}$ becomes antiferromagnetic and can be correlated to that of NI. In addition, the ferromagnetic ^4A ground state of $\mu_3\text{O}$ is found from variable-temperature EPR to undergo a zero-field splitting (ZFS) of $2D = -5.0 \text{ cm}^{-1}$, which derives from the second-order anisotropic exchange. This allows evaluation of the σ -to- π excited state exchange pathways and provides experimental evidence that the orbitally-degenerate ^2E ground state of the antiferromagnetic $\mu_3\text{O}$ would also undergo a ZFS by the first-order antisymmetric exchange that has the same physical origin as the anisotropic exchange. The important contribution of the μ_3 -oxo bridge to the ground-to-ground and ground-to-excited state superexchange pathways that are responsible for the isotropic, antisymmetric and anisotropic exchange are discussed.

Introduction

Trimeric copper complexes with trigonal symmetry have attracted significant interest as these complexes resemble the active sites of the multicopper oxidases (MCO) which include laccase, ascorbate oxidase and ceruloplasmin.¹ The fully reduced forms of these enzymes react with O_2 to form the native intermediate (NI) that has a fully oxidized antiferromagnetically coupled trinuclear Cu^{II} cluster in which all Cu centers are bridged by the product of full O_2 reduction.² It has been suggested that the bridged structure results in new signals in the electron paramagnetic resonance (EPR) spectrum with g -values of 2.15, 1.86 and 1.65, the latter two being < 2.0 .² In addition, a low-lying excited doublet state exists $\sim 150 \text{ cm}^{-1}$ above the ground doublet state as determined from EPR power saturation and variable-temperature (VT) magnetic circular dichroism (MCD) spectroscopies.²

Two limiting structures for the trinuclear Cu^{II} site in NI are consistent with its reactivity and spectral features.^{1,2} The first structure has three μ_2 -OH ligands, each bridging a Cu^{II} pair where two OH⁻ ligands derive from O_2 and the third from an ambient H_2O (Chart 1(a)); the second structure has a single μ_3 -oxo ligand bridging all three Cu^{II} centers of the cluster with the second O atom from O_2 reduction, either remaining bound or dissociated from the trinuclear site (Chart 1(b)). Recently, we have reported the ground state properties of the first structure using a D_3

symmetric model complex, TrisOH.^{3,4} In TrisOH, all Cu^{II} pairs are antiferromagnetically coupled, yielding a ²E ground state with a zero-field splitting (ZFS) of 65 cm⁻¹. Moreover, a strongly anisotropic EPR signal, which shifts in resonance field with g_{eff} values from 2.32 to ~1.2, was observed in the single crystal EPR spectrum.³ These characteristic features of the ²E ground state of TrisOH arise from the combined effect of symmetry lowering, which reflects a magnetic Jahn-Teller distortion, and antisymmetric exchange,⁵ which results from first-order spin-orbit coupling (SOC) to an excited state and excited-to-ground state superexchange interactions. In particular, the low g_{eff} values < 2.0 are due to the antisymmetric exchange which allows field induced mixing between the two ZFS doublets of the ²E ground state when the molecular z-axis (normal to the Cu₃ plane) is oriented perpendicular to the magnetic field.⁶ We have shown that the structure of TrisOH is well suited for antisymmetric exchange as it provides efficient local $d_{x^2-y^2}$ -to- d_{xy} SOC as well as the pathways for ground-to-excited state superexchange interactions between the $d_{x^2-y^2}$ ground state of one Cu center with the d_{xy} excited state of another Cu center through the Cu-OH σ -bonds.³

The ground state properties of the second possible structure of NI can be best studied using the C₃-symmetric Cu₃^{II} complex (μ_3 O, Figure 1) synthesized by Suh et al.⁷ μ_3 O is the only μ_3 -oxo bridged Cu₃^{II} complex without other effective bridging ligands, such as pyrazolates,⁸ that may significantly affect the exchange coupling.⁹ The distances between the Cu^{II} centers of the two neighboring trimer units is large enough (closest being 9.67 Å) to avoid significant intermolecular interactions. Moreover, μ_3 O exists in a protonated form, μ_3 OH, that has been also determined to be C₃ symmetric. Thus, the bonding interactions between the μ_3 -oxo ligand and the Cu^{II} centers can be greatly simplified, and the protonated μ_3 OH form can be used as a perturbation of the μ_3 O structure. However, μ_3 O has a ferromagnetic ⁴A ground state ($J = +54.5$ cm⁻¹),⁷ inconsistent with the ground state of NI. A possible reason for this difference is that the oxo-ligand lies ~0.5 Å above the Cu₃ plane in μ_3 O. However, as the trinuclear Cu^{II} site in NI has a more flexible ligand environment, the oxo-ligand is expected to be less protruded above the Cu₃ plane than in μ_3 O which has a relatively rigid, bowl-shaped macrocyclic ligand.¹⁰

This study focuses on the ground state electronic and magnetic properties of the μ_3 O structure. First, the Cu-O bonding interactions in the ferromagnetic μ_3 O and its protonated form, μ_3 OH, are evaluated using the combination of EPR spectroscopy and DFT calculations. Then, a set of DFT calculations evaluating the effect of the position of the oxo-ligand relative to the Cu₃ plane is presented, which allows correlation to the antiferromagnetic ground state of NI. In addition, the orbitally non-degenerate ⁴A ground state of μ_3 O can ZFS into M_S = $\pm 1/2$ and $\pm 3/2$ doublets via SOC that derives from second-order anisotropic exchange (see below). As the anisotropic exchange shares the same physical origin as the antisymmetric exchange, the evaluation of the contributions of the μ_3 -oxo bridging ligand to both the ground-to-ground and ground-to-excited state superexchange interactions would provide insight into the ground state properties of both the ferromagnetically and antiferromagnetically coupled μ_3 -oxo bridged trimeric Cu^{II} systems and allow extension to the ground state properties of NI.

Experimental Section

Detailed descriptions of the syntheses, crystal structures and magnetic susceptibilities of μ_3 O and its protonated form, μ_3 OH, are as reported.⁷

EPR spectra were obtained using a Bruker EMX spectrometer. For X-/Q-band experiments, Bruker ER 041XG/ER 051QR microwave bridges and ER 4102ST/ER 5106QT cavities were used. Temperatures from 3.65 K to 120 K were maintained using an Oxford ITC503 temperature controller with an ESR 900 Continuous Flow Cryostat for X-band and a CF935 Dynamic Continuous Flow Cryostat for Q-band (transfer line GFS650 from Oxford

Instruments). The powder samples were prepared anaerobically by finely grinding the single crystals of $\mu_3\text{O}$ and $\mu_3\text{OH}$ under a N_2 atmosphere in a glove box. EPR spectra were baseline subtracted and simulated using XSophe (Brüker).¹¹

Spin-unrestricted DFT calculations were performed using Gaussian 98¹² and Amsterdam Density Functional (ADF)¹³ programs and the results were analyzed using AOMix.¹⁴ All geometry optimizations were performed at uB3LYP/Lanl2dz level.¹⁵ For both $\mu_3\text{O}$ and $\mu_3\text{OH}$, all the ethylene groups linking N-atoms in the macrocyclic ligand were truncated with H atoms (Figure 1) and geometry optimized in C_3 symmetry with $\langle S^2 \rangle \approx 3.75$. The resulting geometries were then used for single-point calculations with a triple- ζ Slater-type orbital basis set (ADF basis set TZP) with a single polarization function at the local density approximation of Vosko, Wilk, and Nusair¹⁶ with non-local gradient corrections of Becke and Perdew.¹⁷

Results

Electron Paramagnetic Resonance

(a) $\mu_3\text{O}$ —The EPR spectra of the powder $\mu_3\text{O}$ sample taken at X-band (9.390 GHz = 0.313 cm^{-1} , 8 K) and Q-band (33.81 GHz = 1.13 cm^{-1} , 10 K) are presented with their simulated spectra in Figure 2. The EPR signals in X-band are observed only below 120 K and their intensities reach their maxima near 8 K. No change in the spectral shape is observed over the temperature range of 3.73 to 120 K (Figure S1). Two transitions at g_{eff} of 3.64 and 2.06 in X-band and 3.77 and 2.06 in Q-band are observed with no discernable hyperfine feature. These transitions correspond to the “ $g = 4$ ” and “ $g = 2$ ” resonances of an axial zero-field split quartet ($S_{\text{tot}} = 3/2$) system demonstrating a ferromagnetic ground state, consistent with magnetic susceptibility data⁷ (the energy level is shown in Scheme 1). If the two Kramers doublets originating from the zero-field splitting (ZFS) of the ^4A ground state are well separated in energy such that the intermixing of these states can be ignored, then the $g_{\text{eff}} \sim 4$ resonance is equal to twice the true $g_{x,y}$ of the molecule, which, in turn, corresponds to the vector coupled g -values of the individual Cu sites in the trimer.¹⁸ However, with the g_{eff} of 3.64/3.77 (X-/Q-band), the molecular $g_{x,y}$ would be 1.82/1.89 which is too low for the individual Cu centers in $\mu_3\text{O}$. Therefore, the g_{eff} values indicate that the ZFS of the ground state is small enough that the doublets mix with applied magnetic field.

In order to evaluate the molecular g -values and the ZFS of the ground state, simulations were performed simultaneously on the X- and Q-band EPR spectra using the spin-Hamiltonian:

$$\hat{H}_{\text{spin}} = \beta H \cdot \bar{g} \cdot \hat{S} + \hat{S} \cdot \bar{D} \cdot \hat{S} \quad (1)$$

where β is the Bohr magneton, H is the magnetic field, $\bar{g}$ is the g -tensor in which $g_{xx} = g_{yy} \neq g_{zz}$, $g_{ij} = 0$ ($i \neq j$), $\hat{S}$ is the electron spin operator and $\bar{D}$ is the D -tensor in which $D_{xx} = D_{yy} = -\frac{1}{2}D_{zz}$ ($= -D/3$) and $D_{ij} = 0$ ($i \neq j$). The best simulated spectra were obtained with $g_x = g_y = 2.021$ (± 0.010), $g_z = 2.064$ (± 0.005), with line width parameters $W_{x,y,z} = (650 \text{ G}, 650 \text{ G}, 280 \text{ G})$ and the ZFS D - E strain parameters σ_D and σ_E of 0.06 and 0.07, respectively (Figure 2). The D -value could not be quantitatively obtained, but the lower limit of its magnitude is $|D| > 2.0 \text{ cm}^{-1}$.

The magnitude and the sign of the D -value were obtained from the temperature dependent behavior of the EPR intensities. Figure 3 gives a plot of the normalized EPR intensities (at several fields in X-band) against $1/T$ in non-saturating conditions. Assuming the ZFS is sufficiently large so that no transition is made between the two zero-field split Kramer doublets of the ^4A ground state and that the plotted EPR intensities are purely from the transition between

the $M_S = \pm 1/2$ components, a Boltzmann fit to the Curie law dependence was performed using eq 2:

$$\text{EPR Intensity} = \frac{C}{T} \left(\frac{\exp(-2D/kT)}{1 + \exp(-2D/kT)} \right) \quad (2)$$

where C is Curie constant, T is the temperature in K, D is the axial ZFS parameter and k is Boltzmann's constant. The best fit gives $D = -2.5 \pm 0.1 \text{ cm}^{-1}$.

The energy levels are linearly dependent on field when the molecular z -axis is aligned with the field, but not linearly dependent when the field is perpendicular to the molecular z -axis (Figure S2). The non-linearity in the latter case results from the interaction of the upper and lower doublets of the ZFS 4A ground state and this gives g_{eff} values less than 4 (Figure 2). However, the ZFS ($= 2D$) of -5.0 cm^{-1} is large enough so that no transition between the two ZFS doublets occurs with the X- or Q-band energy. This large ZFS originates from the anisotropic exchange (also called pseudo-dipolar exchange) involving the ground-to-excited superexchange interaction between an electron in the ground (d_{z^2}) and the excited ($d_{x^2-y^2}$) states (see below). The spin-spin dipolar contribution to ZFS is much smaller in magnitude ($|D_{dd}| = 0.27 \pm 0.01 \text{ cm}^{-1}$) as obtained from a point dipole model in which $|D_{dd}| \approx 0.650 g^2/r^3$.¹⁹

The calculated molecular g -values from these simulations can be directly correlated to the local g -values of each Cu center: $(g_x, g_y) \sim (g_{x'}, g_{y'})$ and $g_z \sim g_{z'}$, where the primed axes (x', y', z') refer to the local coordinates of the Cu sites and the non-primed axes (x, y, z) refer to the $\mu_3\text{O}$ molecular coordinates with z as the direction perpendicular to the Cu_3 plane (Figure 1). The $g_z \sim g_{y'} = 2.064$ is small compared to the typical $g_{\perp}$ -value of a trigonal pyramidal mononuclear Cu-complex of ~ 2.2 .²⁰ This is consistent with the large covalency of the Cu-oxo bonds. A significant orbital reduction would result in the low observed g -value, as compared to those of Cu complexes with relatively weak Cu-to-ligand bonding interactions.

(b) $\mu_3\text{OH}$ —The EPR spectra of the powder $\mu_3\text{OH}$ sample taken at X-band (9.390 GHz, 8 K) and at Q-band (33.95 GHz, 10 K) are presented with their simulated spectra in Figure 4. The EPR signals in the X-band are observed only below 120 K and their intensities increase as the temperature is lowered. No change in the spectral shape was observed over the temperature range of 3.65 to 120 K (Figure S3). In the X-band spectrum, features are observed at g_{eff} of 3.70 and 2.22 with no discernable hyperfine structure. As with $\mu_3\text{O}$, these correspond to the “ $g = 4$ ” and “ $g = 2$ ” resonances of an axial ZFS quartet system with a ferromagnetic ground state, consistent with magnetic susceptibility data.⁷ In the Q-band spectrum, more than two resonances are observed (Figure 4(b)). Here, while the “ $g = 4$ ” and “ $g = 2$ ” resonances are still observed at g_{eff} of 3.75 and 2.22, additional signals are present at 4360 G ($g_{\text{eff}} \sim 5.57$) and between 8000 to 10000 G.

Simulations were performed simultaneously on the X- and Q-band spectra using the spin-Hamiltonian of eq 1. The best simulated spectra were obtained with $g_x = g_y = 2.067 (\pm 0.010)$, $g_z = 2.224 (\pm 0.005)$, with the line width parameters $W_{x,y,z} = (580 \text{ G}, 580 \text{ G}, 330 \text{ G})$ and the ZFS D - E strain parameters σ_D and σ_E of 0.05 and 0.03, respectively (Figure 4). Here, the magnitude of the D -value of 1.02 cm^{-1} could be obtained as the new signal at $g_{\text{eff}} \sim 5.57$ is very sensitive to this value. The sign of the D -value could be obtained from the plot of the normalized X-band EPR intensities against $1/T$, which is presented in the inset of Figure 3. Using eq 2, the best fit gives $D = -0.8 \pm 0.2 \text{ cm}^{-1}$.

As with $\mu_3\text{O}$, the energy levels are linearly dependent on field where the molecular z -axis is aligned with the field, but not linearly dependent when the field is perpendicular to the molecular z -axis (Figure S4). Again, the non-linearity of the latter case results in the g_{eff} values less than 4 (Figure 4). However, the ZFS is smaller than that of $\mu_3\text{O}$ and is comparable to the Q-band energy. As a result, transitions between the doublets are observed. In particular, the $\Delta M = \pm 2$ transition becomes allowed that is observed at g_{eff} of 5.57 (Figure 4(b)). The small ZFS, as compared to that of $\mu_3\text{O}$, reflects a decreased anisotropic exchange, indicating that the ground-to-excited exchange interactions have become smaller (see below). The spin-spin dipolar contribution to ZFS in $\mu_3\text{OH}$ ($|D_{\text{dd}}| = 0.26 \pm 0.02 \text{ cm}^{-1}$) is again much smaller in magnitude than the observed ZFS of -2.04 cm^{-1} .

The molecular g_z -value of 2.224 that corresponds to the g_y of the local Cu site is similar to the typical $g_{\perp}$ -value of a trigonal pyramidal mononuclear Cu-complex. This demonstrates that the Cu-OH bonds in $\mu_3\text{OH}$ are much less covalent compared to the Cu-O bonds in $\mu_3\text{O}$. This difference in Cu-O bond covalency is also reflected in the superexchange interactions in these complexes as the magnitudes of the coupling constants (e.g. isotropic exchange constant J ; $+54.5 \text{ cm}^{-1}$ for $\mu_3\text{O}$ and $+18.9 \text{ cm}^{-1}$ for $\mu_3\text{OH}$)⁷ depend on the exchange integrals which are largely related to orbital overlap.

Analysis

Spin-unrestricted DFT calculations were performed on $\mu_3\text{O}$ and its protonated form, $\mu_3\text{OH}$, where all the ethylene groups linking N-atoms in the macrocyclic ligand have been truncated with H atoms as shown in Figure 1. Atomic labels and the axis systems used throughout the manuscript are described in Figure 1: the primed axes (x_i', y_i', z_i') refer to the local coordinates of the i th Cu site and the non-primed axes (x, y, z) refer to the molecular trimer coordinates where z is the direction perpendicular to the Cu_3 plane. These models were fully optimized in the high-spin quartet state ($\langle S^2 \rangle \approx 3.75$) at the uB3LYP/LanL2Dz level (in Gaussian 98), both resulting in C_3 symmetric structures with the structural parameters given in Table 1 (molecular coordinates given in Tables S1 and S2). Overall, these optimized structures are in good agreement with the crystal structures. The geometry of each Cu site in both models is best described as a distorted trigonal bipyramidal structure which yields a d_{z^2} ground state. The calculated Cu-O and Cu-Cu distances are slightly larger than experiment, likely due to the relaxed ligand structure from the truncation of the ethylene links in the original ligand system. The Cu-O distance in the $\mu_3\text{OH}$ model is $0.13 \text{ \AA}$ longer than that of the $\mu_3\text{O}$ model ($2.10 \text{ \AA}$ vs. $1.97 \text{ \AA}$) which reflects the weakening of the Cu-O bond due to the protonation at the oxo-ligand.

These optimized geometries were further employed for the spin-unrestricted BP86 calculations (in ADF) using the triple- ζ Slater-type orbital basis set (ADF basis set TZP). Single-point calculations were performed in both the quartet and the broken-symmetry ($M_S = 1/2$, $\langle S^2 \rangle \approx 1.75$) states. The broken-symmetry method uses the $M_S = 1/2$ configurations of the trimer ($|\alpha_1\alpha_2\beta_3\rangle$, $|\alpha_1\beta_2\alpha_3\rangle$, $|\beta_1\alpha_2\alpha_3\rangle$, $|\alpha_1\beta_2\beta_3\rangle$, $|\beta_1\alpha_2\beta_3\rangle$ or $|\beta_1\beta_2\alpha_3\rangle$ where 1-3 refer to metal centers and α, β refer to up and down spins) to provide a better estimate of the multi-determinant doublet state ($S_{\text{tot}} = 1/2$, $\langle S^2 \rangle \approx 0.75$) energy than can be obtained from a full-symmetry calculation using the single-determinant DFT approach.²¹ The relative energies of the quartet, the broken-symmetry and the doublet states are described in Scheme 2. Accordingly, the total energy difference of the two single-determinant quartet and the broken-symmetry states can be used to estimate the isotropic exchange constant J ($= \frac{1}{2}(E_{\text{BS}} - E_{\text{HS}})$ where E_{BS} and E_{HS} refer to the total energy of a broken-symmetry and quartet states, respectively) and in turn, the quartet-doublet splitting energy $3|J|$. Table 2 gives the total energies of the $\mu_3\text{O}$ and $\mu_3\text{OH}$ models and the corresponding J values. The J 's obtained indicate ferromagnetic quartet ground

states for both structures with the value for $\mu_3\text{O}$ being considerably higher, in agreement with the experimental results from EPR (above) and magnetic susceptibility.⁷

The features of the MO energy level diagram relevant to the Cu-O bonding interactions in $\mu_3\text{O}$ are presented in Figure 5 for both the quartet and the broken-symmetry states. The MOs are labeled with superscripts (x, y, z , indicating the associated O p -orbital) to facilitate the correlation between the quartet and the broken-symmetry states. The energies and % Cu/O compositions of the MOs are listed in Tables 3 and 4. In addition, the contours of the unoccupied MOs in the high spin and the broken-symmetry states are presented in Figures 6 and 7, respectively. In the quartet state, the MOs are categorized into four types: (1) the metal-based acceptor MO with the out-of-plane O $2p_z$ -orbital character (β_{123^z}), (2) the metal-based acceptor MOs with in-plane O $2p_x$ - or $2p_y$ -orbital characters ($\beta_{124^y}/\beta_{125^x}$), (3) the donor MO based on the out-of-plane O $2p_z$ -orbital (β_{107^z}) and (4) the donor MOs based on the in-plane O $2p_x$ and $2p_y$ -orbitals ($\beta_{104^x}/\beta_{105^y}$). The MOs associated with the in-plane O p_x/p_y orbitals are degenerate with e ($= e_x/e_y$) symmetry in C_3 ($\beta_{104^x}/\beta_{105^y}$ and $\beta_{124^y}/\beta_{125^x}$) whereas those associated with the out-of-plane O p_z orbital are non-degenerate with a symmetry (β_{107^z} and β_{123^z}). In the broken-symmetry state (Figure 5, right), the a - and e -MOs are mixed: the orbital shapes of $\alpha_{123^{y+z}}$, $\alpha_{125^{y-z}}$, $\beta_{123^{y-z}}$, and $\beta_{124^{y+z}}$ are the result of the a and e_y orbital mixing, whereas those of α_{124^x} and β_{125^x} are mainly e_x . The $\alpha_{125^{y-z}}$ of the broken-symmetry state (Figure 7, αLUMO) is mainly localized on one metal and is useful in describing the ligand field around each Cu site. Each five-coordinated Cu^{II} site is best described by a distorted trigonal bipyramidal ligand-field with the relative d -orbital energy order of $d_{z^2} \gg d_{x^2-y^2} > d_{x^2-z^2} \gg d_{y^2-z^2} > d_{xy}$ (Table 5). The two unoccupied β -MOs of the broken-symmetry state, $\beta_{124^{y+z}}$ and β_{125^x} (Figure 7, βLUMO and $\beta\text{LUMO}+1$), reflect the trimeric interactions in the broken-symmetry states (and thus, the doublet state of $\mu_3\text{O}$) and are split in energy by 1500 cm^{-1} (Figure 5, right). The Cu-O bonds in both of these β -MOs are involved in strong σ -interactions as reflected by the large amount of O p -orbital character in these MOs.

The ligand-to-metal bonding interactions of the high-spin state, as described in Figure 6 and Table 3, can be used to describe the superexchange interactions present in $\mu_3\text{O}$. The Cu sites have dominantly d_{z^2} ground state forming either σ or pseudo- σ antibonding MOs with the O $2p$ orbitals. In the quartet ground state ($S_{\text{tot}} = 3/2$ in Figure 5), the degenerate β_{124^y} and β_{125^x} have considerable in-plane O $2p_y$ and $2p_x$ character (20 % each, Table 3), respectively, reflecting strong oxo σ -bonds with the metal d_{z^2} orbitals. The non-degenerate β_{123^z} contains the out-of-plane O $2p_z$ (22 %, Table 3) that forms pseudo- σ bonds with all three metal d_{z^2} as a consequence of the oxo being out of the Cu_3 plane by $\sim 0.5\text{ \AA}$. The pseudo- σ bonds in the a -MO ($= \beta\text{LUMO}$) lead to its destabilization. Consequently, the energy gap between the a - and e - ($= \beta\text{LUMO}+1$) acceptor MOs is reduced and the resulting energy gap of 2450 cm^{-1} (Figure 5, left) is small enough for the ferromagnetic contribution to dominate over the antiferromagnetic contribution, leading to a quartet ground state (see below). Note also that the symmetries of β_{124} and β_{125} MOs (Figures 6 and 7) suggest that the $d_{x^2-z^2}$ excited-state orbitals should have π -type bonds with the in-plane oxo p -orbitals. These bonds would provide effective ground-to-excited superexchange interactions that lead to higher order exchange interactions, in particular, anisotropic exchange, that yields ZFS of -5.0 cm^{-1} in the ^4A ground state of $\mu_3\text{O}$ (see below).

The contours of the unoccupied β -spin acceptor MOs of the protonated $\mu_3\text{OH}$ model in the high-spin quartet state are presented in Figure 8; their orbital energies and % MO compositions are listed in Table 3. The energy gap between the a - ($= \beta\text{LUMO}$) and the e -MOs ($= \beta\text{LUMO}+1$) is similar to that of $\mu_3\text{O}$ (2450 cm^{-1} ($\mu_3\text{O}$) vs. 2100 cm^{-1} ($\mu_3\text{OH}$)) and as a consequence, the ground state of $\mu_3\text{OH}$ is also a ferromagnetic quartet state (Table 2). However, a considerable reduction of both the σ - and pseudo- σ interactions between Cu-O bonds is found: in the $\beta_{124^y}/\beta_{125^x}$ -MOs, the in-plane O $2p_y/2p_x$ characters are reduced by half (from 20 %

to 11 % each; Table 3) and in the $\beta 123^2a$ -MO, the out-of-plane O $2p_z$ character is essentially eliminated (from 22 % to 1 %; Table 3). Moreover, the magnitude of the calculated ferromagnetic J for $\mu_3\text{OH}$ is considerably reduced as compared to $\mu_3\text{O}$ (Table 2). This decrease in J is due to the reduction of the ferromagnetic contribution; the decreased oxo characters in the a - and e -MOs represent the reduction of the spin density overlap between the orthogonal magnetic orbitals.²² Alternatively, the antiferromagnetic contribution remains virtually unaffected since the energy gap between the βLUMO and $\beta\text{LUMO}+1$ is similar to that of $\mu_3\text{O}$ as both of these MOs are shifted in energy by a similar amount from decreased Cu-O interactions due to protonation.

Note that due to the decrease in the Cu-O interactions in $\mu_3\text{OH}$ (between the Cu d_{z^2} and the O $p_{x,y,z}$ -orbitals), the energy gap between the d_{z^2} ground state and the rest of the d -manifold is reduced relative to that of the $\mu_3\text{O}$ model (Table 5). This is experimentally observed in absorption and MCD spectra in which the d-d transition energies are lower for $\mu_3\text{OH}$.²³ The effect of protonation is also reflected in the large stabilization of the O-based donor MOs, which are lowered in orbital energy by 10800 cm^{-1} (Op_x/Op_y) and 27300 cm^{-1} (Op_z) relative to the LUMOs, resulting in the large increase in energy of the associated charge transfer transitions.²³

Finally, the effect of the position of the oxo-ligand relative to the Cu_3 plane on the superexchange interaction was evaluated by varying the oxo-to- Cu_3 plane distance.²⁴ Table 6 lists the resulting structural parameters, orbital energies of the βLUMO and $\beta\text{LUMO}+1$ of the high-spin state, J values and the % MO compositions of the magnetic orbitals obtained from the broken-symmetry calculations. The most conspicuous feature found in these calculations is that the J 's vary significantly from -100 cm^{-1} to $+285\text{ cm}^{-1}$ and that the antiferromagnetic ground state is favored when the distance of the oxo-ligand out of the Cu_3 plane, $R(\text{O}-\text{Cu}_3\text{ plane})$, is smaller than $0.3\text{ \AA}$, while ferromagnetic ground state is favored when $R(\text{O}-\text{Cu}_3\text{ plane})$ is larger than $0.3\text{ \AA}$ (Figure 9(a)).²⁵ This variation in J is not related to either the Cu-Cu/Cu-O distances or the Cu-O-Cu bridging angles as these parameters do not significantly change over the different $R(\text{O}-\text{Cu}_3\text{ plane})$ values.

In particular, the Cu-O-Cu bridging angles, typically used as a criterion for assessing the magnetic properties of dimeric Cu^{II} complexes, appear to play less of a role for $\mu_3\text{O}$ as the angles obtained of 108.6° - 120.0° (Table 6(a)) are in the range that would generally favor a large antiferromagnetic interaction in dimeric Cu^{II} complexes; the Cu-O-Cu angles of $\sim 112^\circ$ in the $\mu_3\text{O}$ crystal structure corresponds to a strongly antiferromagnetic J of $\sim -500\text{ cm}^{-1}$.²⁶ This difference between dimers and the μ_3 -oxo trimers is related to the fact that the antiferromagnetic contribution in Cu^{II} dimers depends on the bonding interactions between the Cu d - and the in-plane OH p -orbitals in the singly-occupied MO (= SOMO) and SOMO +1; the OH p_y - and p_x -orbitals (perpendicular and parallel to the Cu-Cu direction, respectively) each form two Cu-O bonds in the SOMO and SOMO+1. The dependence of J on the Cu-O-Cu angle for the Cu^{II} dimers is thus a consequence of the difference in the in-plane $d-p_y-d$ and $d-p_x-d$ overlaps. However, for the $\mu_3\text{O}$ trimer, the high-spin SOMO and the degenerate SOMO +1 (βLUMO and $\beta\text{LUMO}+1$; Figure 6) involve the out-of-plane O p_z -orbital and the in-plane O $p_{x,y}$ -orbitals, respectively, and therefore, the two dimensional Cu-O-Cu angle is not sufficient for assessing exchange interactions in $\mu_3\text{O}$.

In contrast to the effect of protonation described above, the ferromagnetic contribution, which is largely dependent on the contribution of orthogonal magnetic orbitals to a single center (*i.e.* oxo), is expected to be unaffected as the oxo characters in the magnetic orbitals remain relatively invariant at different $R(\text{O}-\text{Cu}_3\text{ plane})$ distances (Table 6(c)). Alternatively, the energy gap ($E_{\beta\text{LUMO}} - E_{\beta\text{LUMO}+1}$) becomes large when J becomes small. This reciprocal nature of J and ($E_{\beta\text{LUMO}+1} - E_{\beta\text{LUMO}}$) has been recognized by Hay *et al.*²⁷ According to their model,

J has a linear relationship with the SOMO-SOMO+1 energy gap squared, assuming the ferromagnetic contribution remains constant.²⁷

The calculated J 's and the corresponding $(E_{\beta\text{LUMO}+1} - E_{\beta\text{LUMO}})^2$ are plotted in Figure 9(b) in which a linear fit is obtained with a ferromagnetic contribution of $+335\text{ cm}^{-1}$ and an antiferromagnetic contribution of $-(E_{\beta\text{LUMO}+1} - E_{\beta\text{LUMO}})^2/85900\text{ cm}^{-1}$. The denominator in the latter term ($85900\text{ cm}^{-1} \sim 10.5\text{ eV}$) is reasonable as this energy is the energy of the metal-to-metal charge transfer (MMCT) state which is related to the Coulomb repulsion energy of the paired electrons in the MMCT state and has been estimated to be in the range of 5-10 eV.^{28,29} Thus, change in the exchange coupling interaction when the oxo-ligand is moved into the Cu_3 plane is dominantly dependent on the change in the antiferromagnetic contribution that is determined by the energy gap between the βLUMO and $\beta\text{LUMO}+1$. When the oxo-ligand is moved out of the Cu_3 plane, the pseudo- σ overlap between Cu d_{z^2} and the out-of-plane oxo p_z orbitals increases. Consequently, the antibonding βLUMO (the $a\text{-MO}$; Figure 6) is destabilized and its energy gap with $\beta\text{LUMO}+1$ (the $e\text{-MO}$; Figure 6) is decreased, and thus, reduces the antiferromagnetic contribution relative to the ferromagnetic contribution. This results in the experimentally determined J of $+54.5\text{ cm}^{-1}$ for the $\mu_3\text{O}$ complex in which the R (O- Cu_3 plane) is $\sim 0.5\text{ \AA}$. Conversely, moving the oxo-ligand into the Cu_3 plane (R(O- Cu_3 plane) $< 0.3\text{ \AA}$) results in antiferromagnetically coupled system due to loss of the pseudo- σ interactions in the βLUMO that leads to its decreased destabilization and increased $(E_{\beta\text{LUMO}+1} - E_{\beta\text{LUMO}})$ energy gap.

Discussion

In this study, experimental and computational perturbations on the $\mu_3\text{O}$ structure, protonation of the oxo-ligand and variation of the oxo-to- Cu_3 plane distance, have been performed to evaluate the behavior of the μ_3 -oxo bridging ligand in the exchange coupling of the three Cu^{II} centers in the $\mu_3\text{O}$ complex. DFT analysis has shown that the difference in the magnitude of J between $\mu_3\text{O}$ and its protonated form, $\mu_3\text{OH}$, arises from the large decrease in the Cu^{II} -oxo bonding interactions upon protonation. Consequently, the ferromagnetic contribution to the exchange coupling is reduced, which reflects the decrease in the spin density contributions from the orthogonal magnetic orbitals of the three metal centers to the bridging ligand. However, the $(E_{\beta\text{LUMO}+1} - E_{\beta\text{LUMO}})$ energy gap, and hence, the antiferromagnetic contribution, shows little change upon protonation as both orbitals are stabilized in energy by the reduced Cu-O bonding interactions. Alternatively, upon moving the oxo-ligand close to the Cu_3 -plane, the antiferromagnetic contribution is greatly increased and dominates over the relatively constant ferromagnetic contribution. This is a consequence of the reduction of the pseudo- σ bonding interactions between the Cu d_{z^2} and the out-of-plane oxo p_z orbitals which increases the βLUMO and $\beta\text{LUMO}+1$ energy splitting. With the decrease of the d_{z^2} - p_z interactions, the ground state of $\mu_3\text{O}$ becomes an antiferromagnetic ^2E state when the oxo-to- Cu_3 plane distance is less than $\sim 0.3\text{ \AA}$. Note that the trinuclear Cu cluster site in the multicopper oxidases (MCO) is less rigid than the bowl-shaped macrocyclic ligand of $\mu_3\text{O}$. Therefore, if the trinuclear Cu cluster site in the native intermediate (NI) of the MCOs has a μ_3 -oxo bridged structure, the central oxo-ligand would likely be positioned close to the Cu_3 plane (from QM/MM geometry optimization of NI),³⁰ resulting in a spin-frustrated doublet ground state as observed experimentally.²

The orbitally degenerate ^2E ground state of an antiferromagnetically coupled $\mu_3\text{O}$ would ZFS by the first-order antisymmetric exchange.³¹ This exchange can be related to the large ZFS in the ferromagnetic ^4A ground state of $\mu_3\text{O}$ that has been experimentally determined here from VT EPR. The ZFS of the ^4A state is governed by the anisotropic exchange (D) which derives from second-order SOC combined with ground-to-excited state exchange coupling.³¹

Importantly, the anisotropic exchange shares the same physical origin as the antisymmetric exchange (G). For a pair of metal centers, these exchange terms are expressed as:

$$G_{12}=2i\lambda\left[\frac{\langle e_1 |L_1 |g_1\rangle}{\Delta_1}(-2J_{g_1g_2}^{e_1g_2})-\frac{\langle e_2 |L_2 |g_2\rangle}{\Delta_2}(-2J_{g_1g_2}^{g_1e_2})\right] \quad (3)$$

$$D_{12}=\lambda^2\left[\frac{\langle e_1 |L_1 |g_1\rangle^2}{\Delta_1^2}(-2J_{e_1g_2}^{e_1g_2})+\frac{\langle e_2 |L_2 |g_2\rangle^2}{\Delta_2^2}(-2J_{g_1e_2}^{g_1e_2})\right] \quad (4)$$

where λ is the SOC parameter, $|g_i\rangle$ and $|e_i\rangle$ are the ground and excited states at the i th metal center, Δ_i is the energy difference between $|g_i\rangle$ and $|e_i\rangle$, L_i is the orbital angular momentum operator that couples $|g_i\rangle$ and $|e_i\rangle$, and $J_{g_1g_2}^{e_1g_2}$, $J_{g_1g_2}^{g_1e_2}$, $J_{e_1g_2}^{e_1g_2}$ and $J_{g_1e_2}^{g_1e_2}$ are superexchange integrals³² in which, $J_{g_1g_2}^{e_1g_2}$ involves transfer of one electron in the ground state of metal 1 to the ground state of metal 2 and the second electron from the ground state of metal 2 to the excited state of metal 1, while $J_{e_1g_2}^{e_1g_2}$ involves transfer of both electrons between the excited state of metal 1 and the ground state of metal 2. Thus, both the antisymmetric and anisotropic exchanges are derived from (1) local SOC and (2) superexchange coupling between the ground state of one center to the excited state of the other center, and vice versa.

In the $\mu_3\text{O}$ structure, the d_{z^2} ground state at each metal center can SOC with the $d_{xz'}$ excited state via orbital angular momentum operator $L_{y'} \sim L_z$ (local y' axis $\sim$ molecular z axis; Figure 1).³³ Further, the ground-to-excited state superexchange between d_{z^2} and $d_{xz'}$ orbitals of different metal centers is facilitated via the in-plane oxo p -orbitals as superexchange pathways (Scheme 3). The ZFS of -5.0 cm^{-1} in the ^4A ground state in $\mu_3\text{O}$, dominated by the anisotropic exchange contribution (the spin-spin dipolar contribution being less than $\sim 0.3\text{ cm}^{-1}$), provides experimental evidence, in magnitude and sign, for the existence of the combined effects of the local SOC and ground-to-excited state superexchange. Therefore, it is expected that the ^2E ground state of the $\mu_3\text{O}$ structure would also undergo ZFS by the antisymmetric exchange

interaction. The ground-to-excited exchange integral $J_{z_1^2z_2^2}^{xz_1^2xz_2^2}$ should be larger than the ground-to-ground exchange integral $J_{z_1^2z_2^2}^{z_1^2z_1^2z_2^2z_2^2}$ as the ground-to-excited antiferromagnetic coupling is further facilitated by the π -bond between $d_{xz'}$ and the in-plane oxo p -orbital which σ -bonds to d_{z^2} on the adjacent Cu centers, as illustrated in Scheme 3. Using the calculated ground state exchange coupling constant $J_{z_1^2z_2^2}^{z_1^2z_1^2z_2^2z_2^2}$ of -55.2 cm^{-1} ($=J$ when $\text{R}(\text{O}-\text{Cu}_3\text{ plane})$ is 0° ; Table 6) as a lower limit for $J_{z_1^2z_2^2}^{xz_1^2xz_2^2}$, the magnitude of the pairwise antisymmetric exchange parameter $|G_{12}|$ of 42 cm^{-1} can be estimated.³⁴ Thus, the ^2E ground state of $\mu_3\text{O}$ with the oxo-ligand in the Cu_3 plane would exhibit a ZFS of $\sim 70\text{ cm}^{-1}$ ($=\sqrt{3}|G_{12}|$ for the Cu^{II}_3 trimer)⁶ from antisymmetric exchange.

A similar ZFS of 65 cm^{-1} has been experimentally determined in the ^2E ground state of TrisOH which results from the combined effects of symmetry lowering and antisymmetric exchange (see Introduction).³ We have used a spin-Hamiltonian model to show that the antisymmetric exchange SO mixes the two ZFS doublets of the ^2E ground state resulting in low g_{eff} values which shift down to < 1.2 in the perpendicular direction (*i.e.* when the molecular z -axis normal to the Cu_3 plane is oriented perpendicular to the magnetic field).^{3,6} This model is appropriate

for any antiferromagnetically coupled Cu^{II} trimer with near C_3 -symmetry as it does not take into account the specific orbital superexchange pathways involved. Thus, an antiferromagnetically coupled $\mu_3\text{O}$ structure is also expected to produce low g -values in the perpendicular direction as it has efficient ground-to-ground and ground-to-excited state superexchange pathways for antisymmetric exchange.

Therefore, both the μ_3 -oxo bridged and the tris- μ_2 -hydroxy bridged structures would exhibit an unusual $S = 1/2$ EPR signal with low g -values below 2.0. The characteristic EPR signal of NI, which exhibits a low g_{eff} value of ~ 1.65 , can be explained by $\sim 6\%$ SO mixing³⁵ between the ground and the low-lying excited doublet states via antisymmetric exchange among the three Cu^{II} centers in the trinuclear cluster site. The fundamental description of the ground state of the exchange coupled μ_3 -oxo bridged structure in this study and that of the tris- μ_2 -hydroxy bridged TrisOH in ref. 3 allow detailed insight into the nature of the ground state of the native intermediate. This is important with respect to both the molecular mechanism of O-O bond cleavage and the contribution of the superexchange pathways to the facile re-reduction of this fully oxidized intermediate in the turnover of the multicopper oxidases.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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- In the Cu_3 complexes of ref. 8, the additional N=N bridging ligands from the pyrazolates are in the same plane as the magnetic orbitals ($\text{Cu } d_{x^2-y^2}$). Also, the conjugate π -bonds of the N=N would be relatively close in energy to the metal d -orbitals. These conditions would promote effective electron delocalization and spin polarization, and thus, the exchange coupling in these Cu_3 complexes would be considerably affected by the N=N bonds. On the other hand, the N-CH₂-N bridging ligands in the $\mu_3\text{O}/\mu_3\text{OH}$ model complexes are not in the same plane as the magnetic orbitals ($\text{Cu } d_z^2$) and the saturated methylene bridges (-CH₂-) have very stable occupied orbitals with larger energy gaps to the

metal *d*-orbitals. Therefore, contribution of the N-CH₂-N bridging ligands to the exchange coupling in $\mu_3\text{O}/\mu_3\text{OH}$ would be very limited.

10. The full structure of the macrocyclic ligand is given in the supplementary material (Scheme S1).
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24. The geometry optimizations (using uB3LYP/LanL2Dz in the high spin ($S_{\text{tot}} = 3/2$) state; Gaussian 98) were performed on the $\mu_3\text{O}$ model at six different oxo-to-Cu₃ plane distances. C_{3v} symmetry was imposed on these optimizations which showed no significant deviation in geometry from the C_3 symmetry optimized structure (compare Table 1 and $R(\text{O-Cu}_3 \text{ plane}) = 0.504 \text{ \AA}$ in Table 6(a)).
25. The difference in the calculated *J*-values in Table 2 (+246.4 cm⁻¹) and Table 6 (+184.0 cm⁻¹; $R(\text{O-Cu}_3 \text{ plane}) = 0.504 \text{ \AA}$) originates from the different functionals and basis sets used; not likely from the two geometry optimizations as the two geometries are very similar.
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31. Matrices obtained upon application of the spin wave functions of an axial C_3 symmetric trimer with $s_1 = s_2 = s_3 = 1/2$ to the spin-Hamiltonian describing isotropic, antisymmetric and anisotropic exchange terms are given in the supplementary material. It is shown that only the antisymmetric exchange exists in the ²E state, whereas only the anisotropic exchange exists in the ⁴A state.
32. These exchange integrals can be explicitly written as,

$$J_{g_1 g_2}^{e_1 e_2} = \langle \varphi_g^1(1) \varphi_g^2(2) | \hat{H}_{ex} | \varphi_e^1(2) \varphi_g^2(1) \rangle \quad (a)$$

$$J_{g_1 g_2}^{g_1 e_2} = \langle \varphi_g^1(1) \varphi_g^2(2) | \hat{H}_{ex} | \varphi_g^1(2) \varphi_e^2(1) \rangle \quad (b)$$

$$J_{e_1 g_2}^{e_1 g_2} = \langle \varphi_e^1(1) \varphi_g^2(2) | \hat{H}_{ex} | \varphi_e^1(2) \varphi_g^2(1) \rangle \quad (c)$$

$$J_{g_1 e_2}^{g_1 e_2} = \langle \varphi_g^1(1) \varphi_e^2(2) | \hat{H}_{ex} | \varphi_g^1(2) \varphi_e^2(1) \rangle \quad (d)$$

in which the superscripts 1 and 2 refer to the metal centers and 1 and 2 in the parentheses refer to electrons. The exchange Hamiltonian $\hat{H}_{ex}$ includes contributions from both the two electron Coulomb operator $1/r_{12}$ and the superexchange derived from metal-ligand overlaps.

33. Each metal pair in μ_3O has an effective two-fold rotation axis passing through the midpoint of the pair with the axis nearly in the Cu_3 plane. The symmetry rules of the G vectors allow non-zero G component to be oriented perpendicular to the two-fold axis. The collection of these components from the three metal pairs results in $G_z \neq 0$ and $(G_x, G_y) \approx 0$. Since $(G_x, G_y) \approx 0$, exchange interactions between other orbital states (via L_x and L_y) would have negligible contributions in the antisymmetric exchange interaction.
34. If only the d_{z^2} ground to $d_{x'z'}$ excited state SOC is considered, eq 3 can be written as:

$$G_{12} = \frac{4i\lambda \left\langle x' z' 1 \left| L_{1y'} \right| z' 1 \right\rangle}{\Delta_1} \left(-2 \mathcal{J}_{\substack{x' z' 1 z' 2 \\ z 1 z 2}} \right) \quad (e)$$

since $\left\langle x' z' 1 \left| L_{1y'} \right| z' 1 \right\rangle = -\left\langle x' z' 2 \left| L_{2y'} \right| z' 2 \right\rangle$ (see ref. 3 for details). Substituting

$\left\langle x' z' 1 \left| L_{1y'} \right| z' 1 \right\rangle = i\sqrt{3}$, $\Delta_1 = 15000 \text{ cm}^{-1}$ (from absorption/MCD; see ref. 23), the λ (SOC

constant for Cu^{II}) = -830 cm^{-1} , and $\mathcal{J}_{\substack{x' z' 1 z' 2 \\ z 1 z 2}} = -55.2 \text{ cm}^{-1}$, $G_{12} = 42.3 \text{ cm}^{-1}$ is obtained. Note

that the two-center G_{12} is a vector component along the $y' \sim$ molecular z -axis. The effective sum of the three two-center G_{12} in the symmetric trigonal systems equal $\sqrt{3}G_{12} = 73.3 \text{ cm}^{-1}$.

35. The theoretical model used for $TrisOH^3$ included symmetry lowering δ (an equilateral ($J_{12} = J_{23} = J_{31}$ and $\delta = 0$) to isosceles ($J_{12} \neq J_{23} = J_{31}$ and $\delta = J_{12} - J_{23}$) distortion) and antisymmetric exchange factor G ($\approx G_z$) that were varied to match the experimental data ($g = 2.15, 1.86, 1.65$ and ZFS = 150 cm^{-1}).² The experimental g -value of 2.15 was assumed to be the g_{eff} when the molecular z -axis (the axis normal to the Cu_3 plane) is aligned with the applied magnetic field and the g -values of 1.86 and 1.65 were assumed to be g_{eff} when the molecular z -axis was oriented perpendicular to the applied field. The data were fit by fixing the molecular g_z at 2.15 (= highest g -value from experiment) and the molecular $g_{x,y}$ at 2.0; the latter was chosen after several initial trials (small variation from 2.0 had a negligible influence on the fits). δ was varied and G was obtained from the relation

$\Delta (\text{ZFS}) = \sqrt{\delta^2 + 3G^2} = 150 \text{ cm}^{-1}$, from which $\delta = 132 \pm 8 \text{ cm}^{-1}$ and $G = 41 \pm 8 \text{ cm}^{-1}$ were obtained. Given these values, the coefficient of mixing of the low-lying excited doublet state into the ground doublet state (or of the ground doublet state into the low-lying excited doublet state) is obtained from the expression $\left(\sqrt{\frac{1}{2} \left(1 - \frac{\delta}{\Delta} \right)} \right)^2 = 6.2 (\pm 2.5) \%$.

Figure 1.

$\mu_3\text{O}/\mu_3\text{OH}$ models used in the DFT calculations (H-atoms not shown) with the molecular (x , y , z) and the local coordinate axes (x' , y' , z') indicated. The ethylene links in the bowl-shaped macrocyclic ligand were truncated with H atoms for simplification. Refer to Scheme S1 for the full structure of the N-ligand.

Figure 2. EPR spectra of powder $\mu_3\text{O}$ complex and their simulations using $g_x = g_y = 2.021$, $g_z = 2.064$, $D = -2.50 \text{ cm}^{-1}$, $E/D = 0$, line width parameters $W_{x,y,z} = (650 \text{ G}, 650 \text{ G}, 280 \text{ G})$, and the ZFS D - E strain parameters σ_D and $\sigma_E = 0.06$ and 0.07 , respectively. (a) X-band spectrum taken at 0.3 mW , 8.0 K and 9.390 GHz and (b) Q-band EPR spectrum at 0.097 mW , 10.0 K and 33.81 GHz .

Figure 3.

Boltzmann fit to the Curie law for the temperature dependence of the $\mu_3\text{O}$ powder EPR intensities arising from the transitions between $M_S = \pm 1/2$ levels. The dotted line is a least squares fit to the data with ZFS of $2D = -5.0 \pm 0.2 \text{ cm}^{-1}$. (Inset) Similar plot of the $\mu_3\text{OH}$ powder EPR intensities and fit curve with ZFS of $2D = -1.6 \pm 0.4 \text{ cm}^{-1}$.

Figure 4. EPR spectra of powder $\mu_3\text{OH}$ complex and their simulations using $g_x = g_y = 2.067$, $g_z = 2.224$, $D = -1.02 \text{ cm}^{-1}$, $E/D = 0$, line width parameters $W_{x,y,z} = (580 \text{ G}, 580 \text{ G}, 330 \text{ G})$, and the ZFS D - E strain parameters σ_D and $\sigma_E = 0.05$ and 0.03 , respectively. (a) X-band spectrum taken at 0.3 mW , 7.6 K and 9.390 GHz and (b) Q-band EPR spectrum at 0.097 mW , 10.0 K and 33.95 GHz .

Figure 5.

Energy level diagram obtained from DFT calculations on the $\mu_3\text{O}$ model where the dotted horizontal lines indicate unoccupied spin orbitals. Only the MOs relevant to Cu-O bonds are presented. The superscripts (x, y, z) on the orbital numbers refer to the O p -orbital involved in the indicated MO.

Figure 6. Contours of β -spin LUMO ($\beta 123$) and LUMO+1 ($\beta 124$ and $\beta 125$ degenerate) obtained from DFT calculation on the $\mu_3\text{O}$ model in the high spin state $S_{\text{tot}} = 3/2$. (Inset) Side view of $\beta 123$.

Figure 7. Contours of α - and β -spin LUMOs obtained from DFT calculation on the $\mu_3\text{O}$ model in the broken-symmetry $M_S = 1/2$ state. (Insets) Side views of $\alpha 125$ and $\beta 124$.

Figure 8. Contours of β -spin LUMO and LUMO+1 ($\beta 124$ and $\beta 125$ degenerate) obtained from DFT calculation on the $\mu_3\text{OH}$ model in the high spin state $S_{\text{tot}} = 3/2$. (Inset) Side view of $\beta 123$.

Figure 9. (a) Plot of the isotropic coupling constant J 's at different oxo-to- Cu_3 plane distances, $R(\text{O-Cu}_3 \text{ plane})$, and (b) the linear correlation between these J 's and the corresponding $(E_{\beta\text{LUMO}+1} - E_{\beta\text{LUMO}})^2$ as obtained from DFT calculations. Refer to Table 6 for more details.

Scheme 1.
The Ground State Energy Diagram of $\mu_3\text{O}$.

Scheme 2.

Energy splitting in the Ground State of a C_3 Symmetric Trimer with $s_1 = s_2 = s_3 = 1/2$.

Scheme 3.
Ground (d_z^2) to Excited (d_{xz}) State SOC and Superexchange Pathways in $\mu_3\text{O}$.

(a) Tris-OH Bridged **(b) μ_3 -Oxo Bridged**

Chart 1.
Proposed Structures of the Native Intermediate.

Table 1
Structural Parameters of the DFT Optimized $\mu_3\text{O}$ and $\mu_3\text{OH}$ Models.^a

	$\mu_3\text{O}$		$\mu_3\text{OH}$	
	<i>expt.</i> ^b	calc.	<i>expt.</i> ^b	calc.
R(Cu-Cu)	3.105/3.125	3.30	3.262/3.250	3.53
R(Cu-O)	1.869/1.883	1.97	1.966/1.951	2.10
R(Cu-N _{ax}) ^c	2.040/2.044	2.17	2.002/2.014	2.11
R(Cu-N _B) ^c	2.241/2.272	2.21	2.201/2.206	2.21
R(Cu-N _{sl}) ^c	2.138/2.167	2.25	2.105/2.086	2.24
R(Cu-N _{s2}) ^c	2.125/2.099	2.22	2.115/2.141	2.24
R(O-Cu ₃ plane)	0.528/0.539	0.507	0.564/0.537	0.521
A(Cu-O-Cu)	112.3/112.2	113.6	112.1/112.8	114.1

^a uB3LYP/LanL2Dz (Gaussian 98) results are presented in which each structure resulted in C_3 symmetry. Distances are in Å and angles are in degrees (°).

^b Two independent molecules are found in a unit cell.⁷

^c See Figure 1 for atomic labels.

Table 2Total Energies and Isotropic Exchange Constants (J) of the $\mu_3\text{O}$ and $\mu_3\text{OH}$ Models from DFT (ADF) Calculations.^a

	$\mu_3\text{O}$	$\mu_3\text{OH}$
E_{HS}^b	-9.59171035 a.u.	-9.07781061 a.u.
E_{BS}^c	-9.58946495 a.u.	-9.07759694 a.u.
J_{calc}^{de}	+246.4 cm^{-1}	+23.4 cm^{-1}
J_{expt}^f	+54.5 cm^{-1}	+18.9 cm^{-1}

^a uBP86/TZV (ADF) results are presented.^b The total energy (LDA+GGA+XC) of the high-spin ($S_{\text{tot}} = 3/2$) state.^c The total energy (LDA+GGA+XC) of a broken-symmetry ($M_S = 1/2$) state.^d $J = \frac{1}{2}(E_{\text{BS}} - E_{\text{HS}})$; refer to Scheme 2.^e Conversion factor: 1 a.u. = $2.19475 \times 10^5 \text{ cm}^{-1}$.^f Magnetic susceptibility results.⁷

Table 3
Energies and % Cu/O Compositions of $\mu_3\text{O}$ and $\mu_3\text{OH}$ in the High-Spin ($S_{\text{tot}} = 3/2$) State.

Description	β -MO #	Symm. in C_3	E (eV)	RelE (cm^{-1}) ^{a,b}	Cu d_{z^2}	Cu $d_{x^2-y^2}$	Cu d_{xy}	O $2s$	O $2p_x$	O $2p_y$	O $2p_z$
$\mu_3\text{O}$											
acceptors											
$\beta\text{LUMO}+1$	$\beta 125^x$	<i>e</i>	-16.06	2450	23.2	2.8 ^c	27.6	0.0	19.7	0.1	0.0
$\beta\text{LUMO}+1$	$\beta 124^y$	<i>e</i>	-16.06	2450	12.5 ^d	32.9	8.2 ^d	0.0	0.1	19.7	0.0
βLUMO	$\beta 123^z$	<i>a</i>	-16.37	0	16.1	16.1	16.1	0.4	0.0	0.0	21.7
donors											
$\text{O}p_z$	$\beta 107^z$	<i>a</i>	-19.52	-25500	14.5	14.5	14.5	0.1	0.0	0.0	18.2
$\text{O}p_x$	$\beta 105^x$	<i>e</i>	-19.92	-28600	7.4	10.2 ^c	5.9	0.0	29.3	0.1	0.0
$\text{O}p_y$	$\beta 104^y$	<i>e</i>	-19.92	-28600	8.3	5.5	9.7	0.0	0.1	29.3	0.0
$\mu_3\text{OH}$											
acceptors											
$\beta\text{LUMO}+1$	$\beta 125^x$	<i>e</i>	-20.21	2100	24.8	1.4 ^c	26.7	0.0	10.6	0.0	0.0
$\beta\text{LUMO}+1$	$\beta 124^y$	<i>e</i>	-20.21	2100	10.5 ^d	33.9	8.6 ^d	0.0	0.0	10.6	0.0
βLUMO	$\beta 123^z$	<i>a</i>	-20.47	0	18.4	18.4	18.4	1.1	0.0	0.0	1.0
donors											
$\text{O}p_y$	$\beta 93^y$	<i>e</i>	-25.36	-39500	0.9	8.5	7.9	0.0	7.2	25.1	0.0
$\text{O}p_x$	$\beta 92^x$	<i>e</i>	-25.36	-39500	10.6	3.1 ^c	3.6	0.0	25.1	7.2	0.0
$\text{O}p_z$	$\beta 80^z$	<i>a</i>	-27.35	-55600	1.1	1.1	1.1	3.9	0.0	0.0	31.9

^aRelative energies when $\beta\text{-LUMO}$ (orbital #123) is set equal to zero.

^bConversion factor: 1 eV = 8065.54 cm^{-1} .

^c $d_{x^2-z^2}$ character.

^dComprises both d_{z^2} and $d_{x^2-z^2}$ characters.

Table 4
Energies and % Cu/O Compositions of $\mu_3\text{O}$ in the Broken-Symmetry ($M_S = 1/2$) State.

Description	MO #	E (eV)	Cu ₁	Cu ₂	Cu ₃	O 2s	O 2p _x	O 2p _y	O 2p _z
α-spin									
<i>acceptors</i>									
αLUMO	$\alpha 125^{y-z}$	-16.27	2.4	48.1	2.3	0.1	3.7	11.0	3.9
αHOMO	$\alpha 124^x$	-16.94	17.2	8.0	17.4	0.0	16.0	5.6	0.0
$\alpha\text{HOMO-1}$	$\alpha 123^{y+z}$	-17.11	13.9	7.3	13.8	0.0	1.1	3.0	26.0
<i>donors</i>									
Op_z	$\alpha 107^{y-z}$	-19.83	16.3	14.3	15.7	0.2	0.4	1.0	14.3
Op_y	$\alpha 103^{y+z}$	-20.21	12.4	7.3	12.5	0.0	5.6	12.8	10.4
Op_x	$\alpha 102^x$	-20.24	6.7	9.2	6.1	0.0	21.6	6.3	0.0
β-spin									
<i>Acceptors</i>									
$\beta\text{LUMO}+1$	$\beta 125^x$	-16.09	26.1	1.9	25.7	0.0	14.7	4.9	0.0
βLUMO	$\beta 124^{y+z}$	-16.27	23.7	3.0	24.4	0.2	2.4	7.5	9.8
βHOMO	$\beta 123^{y-z}$	-16.96	9.1	21.1	7.4	0.0	2.7	7.7	19.2
<i>Donors</i>									
Op_z	$\beta 106^{y-z}$	-19.92	13.6	13.9	14.2	0.0	0.3	2.6	13.6
Op_x	$\beta 105^x$	-19.95	8.0	12.7	6.0	0.0	16.7	5.3	0.1
Op_y	$\beta 102^{y+z}$	-20.15	8.3	7.8	8.1	0.0	5.3	17.3	3.2

Table 5The *d*-orbital Energies of $\mu_3\text{O}$ and $\mu_3\text{OH}$.^a

	$\mu_3\text{O}$		$\mu_3\text{OH}$	
	E (eV)	Rel. E (cm ⁻¹)	E (eV)	Rel. E (cm ⁻¹)
d_{z^2}	-16.3	0	-20.3	0
$d_{x^2-y^2}$	-17.6	10500	-21.5	9680
$d_{x^2-y^2}$	-18.0	13700	-21.9	12900
d_{xz}	-18.7	19400	-22.6	18600
d_{yz}	-19.0	21800	-22.8	20200

^a Orbital energies of the α -MOs obtained from the broken-symmetry calculations using ADF.

Table 6

(a) Structural Parameters, (b) Orbital Energies and the Isotropic Exchange Constant J 's and (c) Compositions of the Magnetic Orbitals Localized at a Single Cu Site in $\mu_3\text{O}$ at Different Oxo-to- Cu_3 Plane Distances.^a

R(O-Cu ₃ plane)	0.0	0.1	0.2	0.3	0.504 ^b	0.7
(a) Structural Parameters ^{c,d}						
R(Cu-Cu)	3.33	3.33	3.33	3.32	3.30	3.27
R(Cu-O)	1.92	1.93	1.93	1.94	1.97	2.01
R(Cu-N _{ax})	2.14	2.14	2.15	2.16	2.18	2.20
R(Cu-N _B)	2.35	2.39	2.26	2.24	2.21	2.20
R(Cu-N _{s1s2})	2.23	2.24	2.24	2.24	2.24	2.23
A(Cu-O-Cu)	120.0	197.7	118.9	117.7	113.7	108.6
(b) Energies ^d						
$E_{\beta\text{LUMO}+1}$ (eV)	-14.64	-14.55	-14.56	-14.60	-14.72	-14.87
$E_{\beta\text{LUMO}}$ (eV)	-15.33	-15.33	-15.30	-15.24	-15.15	-15.11
$E_{\beta\text{LUMO}+1}-E_{\beta\text{LUMO}}$ (cm ⁻¹)	5570	6290	5970	5160	3470	1940
J (cm ⁻¹)	-55.2	-100.1	-51.2	+28.8	+184.0	+285.4
(c) Compositions of the Magnetic Orbitals ^e (%)						
Cu_2 (d_{z^2}) ^f	62.0	61.9	61.6	61.4	60.9	60.2
O ($p_z + p_{xy}$)	13.1	13.2	13.8	14.4	15.6	16.9

^a uB3LYP/LanL2Dz (Gaussian 98) results are presented. Each structure was optimized in C_{3v} symmetry at high-spin quartet ($S_{\text{tot}} = 3/2$) state. Distances in Å and angles are in degrees (°).

^b R(O-Cu₃ plane) obtained when it was not fixed.

^c See Figure 1 for atomic labels.

^d βLUMO and $\beta\text{LUMO}+1$ refer to the unoccupied $\beta 108$ and $\beta 109/\beta 110$ MOs of the high-spin calculations, respectively.

^e αLUMO ($\alpha 110$) of the broken-symmetry ($M_S = 1/2$) calculation.

^f Compositions of the other two Cu centers in the trimer (Cu1 and Cu3) are less than 1%.