

**X-Ray Magnetic Circular Dichroism Provides Strong Evidence for Tetrahedral Iron in  
Ferrihydrite**

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## **Abstract**

Ferrihydrite is an important iron oxyhydroxide for earth and environmental sciences, biology, and technology. Nevertheless, its mineral structure remains a matter of debate. The stumbling block is whether a significant amount of tetrahedrally coordinated iron is present. Here we present the first X-ray magnetic circular dichroism (XMCD) measurements performed on a well characterized synthetic sample of 6-line ferrihydrite, at both K and L<sub>2,3</sub> energy edges of iron. XMCD results demonstrate unambiguously the presence of tetrahedrally coordinated Fe(III) in the mineral structure, in quantities compatible with the latest extended X-ray absorption fine structure (EXAFS) analyses suggesting a concentration of 20-30%. Moreover, we find an antiferromagnetic coupling between tetrahedral and octahedral sublattices, with the octahedral sublattice parallel to the external magnetic field.

## **Introduction**

Ferrihydrite is a widespread iron oxyhydroxide, which is present in diverse environments including soils, sediments, ground waters and streams, and constitutes the mineral core of ferritin, a vital iron storage protein [Cornell and Schwertmann, 2003; Gossuin *et al.*, 2009; Jambor and Dutrizac, 1998; Lewin *et al.*, 2005; Muller *et al.*, 2005; Rancourt *et al.*, 2001; Schwertmann *et al.*, 1987]. It is one of the first solids to precipitate after mineral weathering and exists only as nanoparticles. Ferrihydrite is considered to be a precursor for more crystalline, larger minerals such as goethite, maghemite, or hematite, and therefore plays a key role in understanding mineralization pathways and more generally the biochemical cycling of iron in the environment [e.g., Barrón *et al.*, 2003; Burleson and Penn, 2006; Coker *et al.*, 2006; Cornell and Schwertmann, 2003; Guyodo *et al.*, 2003; Hochella *et al.*, 2008; Penn *et al.*, 2007]. For example, ferrihydrite is present in acid mine drainages, where it favors the sequestration of contaminants such as arsenic because of its high surface reactivity [e.g.,

*Cornell and Schwertmann, 2003*]. The most common reported forms of ferrihydrite are two-line and six-line ferrihydrite, which are characterized by two and six poorly resolved x-ray diffraction (XRD) peaks, respectively [*Cornell and Schwertmann, 2003; Jambor and Dutrizac, 1998*]. In terms of its magnetic properties, ferrihydrite is considered as an antiferromagnetic mineral with an associated ferromagnetic-like magnetic structure due to uncompensated moments [*Berquo et al., 2007; Gilles et al., 2002; Guyodo et al., 2006; Murad, 1988*]. Nanoparticles of ferrihydrite have low temperature magnetic properties that are characteristic of superparamagnetic systems. This magnetic behavior is also observed in Mössbauer spectra, which have developed sextets only below size-dependent blocking temperatures [*Berquo et al., 2007; Guyodo et al., 2006*]. These spectra are characterized by relatively large hyperfine field distributions inherent to poorly crystalline nanoparticle assemblages, which makes them unsuitable for detailed mineral structure studies.

To date, the mineral structure of ferrihydrite remains fairly elusive, despite considerable research efforts [*Carta et al., 2009; Drits et al., 1993; Eggleton and Fitzpatrick, 1988; Harrington et al., 2011; Janney et al., 2000; 2001; Jansen et al., 2002; Maillot et al., 2011; Manceau, 2009; Manceau and Drits, 1993; Michel et al., 2007; Rancourt and Meunier, 2008; Zhao et al., 1994*]. A key aspect of the problem resides in quantifying the presence - or absence - of a substantial amount of tetrahedrally coordinated Fe(III) in the mineral structure. A recent study proposed a single structure by analyzing the pair distribution function (PDF) derived from direct Fourier transformation of total x-ray scattering [*Michel et al., 2007*]. This model structure incorporates 20% of tetrahedrally coordinated Fe(III) [*Harrington et al., 2011; Michel et al., 2007*]. These studies contradict previous results based on extended x-ray absorption fine structure (EXAFS), which proposed a structure based on mixed phases without tetrahedral Fe(III) [*Drits et al., 1993; Manceau and Drits, 1993*]. However,

according to others, the PDF analysis-based model appears to fail at reproducing the data in reciprocal space [Carta *et al.*, 2009; Manceau, 2009; Rancourt and Meunier, 2008]. Nonetheless, a recent x-ray absorption near-edge structure (XANES) study suggested either the presence of a certain amount of tetrahedral iron or the presence of an asymmetric octahedral coordination [Carta *et al.*, 2009]. More recently, a detailed EXAFS study of well characterized ferrihydrite samples pointed to the presence of a significant amount of tetrahedrally coordinated Fe(III) in the mineral structure, ranging between 20 and 30% [Maillot *et al.*, 2011].

We present results from X-ray magnetic circular dichroism (XMCD) measurements performed on a synthetic sample of 6-line ferrihydrite. XMCD is a synchrotron radiation based technique sensitive to the magnetic properties of materials [Saintavit *et al.*, 2003]. It is element specific and does not depend on the existence of a long-range periodic structure, being thus adapted to low-crystallinity mineral phases and small particle sizes. Because of its high sensitivity to site occupancy, XMCD can be used to prove unambiguously the presence of tetrahedrally coordinated ions in iron oxides or oxyhydroxides [Brice-Profeta *et al.*, 2005; Carvallo *et al.*, 2008, 2010; Coker *et al.*, 2007; Pearce *et al.*, 2006; Sikora *et al.*, 2010]. At  $L_{2,3}$  edges, for instance, XMCD can be interpreted in terms of the Ligand Field Multiplet method in the electric dipole approximation. The essential ingredients of this method are the atomic spherical contributions of the Hamiltonian (i.e., kinetic energy, electron-nucleus Coulomb attraction, electron-electron Coulomb repulsion and spin-orbit coupling) and a non-spherical contribution. In this framework, the spherical terms are nearly identical for all Fe(III) ions, while the non-spherical terms are sensitive to the coordination shell (i.e., number and nature of the neighboring ions, spin and orbit magnetic moments). These terms are, however, practically not sensitive to the environment beyond the coordination shell (i.e., the

crystallographic structure). From what precedes, the XMCD signal can thus basically distinguish contributions from Fe(III) versus Fe(II) ions, Fe(III) ions on octahedral sites versus Fe(III) on tetrahedral sites, and Fe spin and orbit magnetic moments parallel versus antiparallel to the external magnetic field.

The XMCD data obtained on our 6-line ferrihydrite sample are compared to the same data acquired on well characterized maghemite samples. XMCD experiments were carried out both at the L<sub>2,3</sub> and K edges of iron. XMCD recorded at the L<sub>2,3</sub>-edge were acquired on the SIM beam line of the Swiss Light Source (SLS) using the Total Electron Yield (TEY) detection mode, while XMCD recorded at the K-edge were acquired on the ID12 beamline of the European Synchrotron Radiation Facility (ESRF) using the Fluorescence Yield (FY) detection mode. Due to sample availability constraints at the time of measurement, two distinct maghemite reference samples were used at ESRF and SLS with identical crystallinity but slightly different average particle sizes.

### **Sample preparation and characterization**

A well characterized sample of 6-line ferrihydrite (Fh) and two reference maghemite samples (Mh1, Mh2) were synthesized for this XMCD study. All samples were prepared by reproducing thoroughly tested synthesis methods [Cornell and Schwertmann, 2003; David and Welch, 1956; Erbs *et al.*, 2008; Maillot *et al.*, 2011; Vayssieres *et al.*, 1998; Wang *et al.*, 2008]. Following standard practice, all samples were dried as soon as synthesized to prevent any mineral change and stored in sealed containers.

The 6-line ferrihydrite sample (Fh) was prepared by following the method of Erbs *et al.* [2008]. In this procedure, a ferrihydrite suspension was prepared by the controlled addition of

a 0.48 M NaHCO<sub>3</sub> (Mallinckrodt) solution to an equal volume of 0.40 M Fe(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O (Fisher) with vigorous stirring. In this method, the ferric nitrate solution is equilibrated to a specific temperature using a heated water bath [Erbs *et al.*, 2008]. The water bath temperature was maintained at 52°C.

The maghemite reference sample used at SLS (Mh1) was synthesized using well established methods [Cornell and Schwertmann, 2003; David and Welch, 1956] by first preparing 280 mL of a solution of 0.3 M Fe(II) sulphate (Fisher) with deionized Milli-Q water (18.2 MΩ) which was degassed with N<sub>2</sub>, and heated to 90°C. To this solution, 120 mL of degassed 0.27 M KNO<sub>3</sub> (Fisher) in 3.33 M KOH (Mallinckrot) was added dropwise over the course of a few minutes. The reaction solution was maintained at 90°C for an additional 60 minutes with magnetic stirring. The precipitated magnetite was magnetically decanted from the mother liquor, and was allowed to cool and dry in a number of weigh boats. The entire preparation was carried out inside a Coy Laboratory Products anaerobic chamber (N<sub>2</sub> with 4-5 % H<sub>2</sub>) [David and Welch, 1956]. The magnetite particles were then placed within a constant temperature furnace at 250°C for 5 hours under atmospheric conditions, resulting in complete oxidation of magnetite to maghemite [Cornell and Schwertmann, 2003].

The synthesis procedure and full characterization of the maghemite reference sample used at ESRF (Mh2) is described by Maillot *et al.* [2011]. It was prepared at room temperature through complete oxidation by hydrogen peroxide of a synthetic magnetite obtained from aqueous coprecipitation of Fe(II) and Fe(III) at pH=7 in a Jacomex® glove box under N<sub>2</sub> atmosphere (< 50 ppm O<sub>2</sub>) [David and Welch, 1956], following the procedure of Vayssieres *et al.* [1998].

XRD patterns for our three samples are displayed in Figure 1A, while additional characterizations have been described in previous publications [Cornell and Schwertmann, 2003; David and Welch, 1956; Erbs et al., 2008; Maillot et al., 2011; Vayssieres et al., 1998; Wang et al., 2008]. As anticipated, the XRD patterns for our samples have peak positions and intensities expected for ferrihydrite and maghemite.

Further characterization of the 6-line ferrihydrite sample was achieved by measuring its low-temperature magnetic properties, which have been shown to be dependent on particle size and crystallinity [Berquo et al., 2007; Guyodo et al., 2006]. Measurements were performed on dry powders using a high-field vibrating sample magnetometer (VSM) and a magnetic properties measurement system (MPMS). Representative results are shown in Figure 1. As expected from previous studies of 6-line ferrihydrite, our sample has magnetic hysteresis (i.e., an open loop) at 5 K (Figure 1B), with a coercivity ( $B_c$ ) value of about 255 mT, which is comparable to other published data [Guyodo et al., 2006]. In addition, the magnetization does not saturate (i.e., it is not independent of the magnetic field), even in a magnetic field as large as 10 T, as can be expected from an antiferromagnetic mineral. Low-temperature field-cooled (M<sub>fc</sub>) and zero-field cooled (M<sub>zfc</sub>) induced magnetizations were measured with a DC field of 5 mT (Figure 1C). In the M<sub>zfc</sub> experiment, the samples were cooled in zero field prior to measurement. In the M<sub>fc</sub> experiment, the samples were cooled in a 5 mT magnetic field, and the induced magnetization was subsequently measured in the same applied field, during warming to room temperature. The M<sub>zfc</sub> curve has a peak at 60 K, which marks the mean of the thermal unblocking temperature distribution of superparamagnetic particles ( $T_b$ ). The temperature at which M<sub>fc</sub> and M<sub>zfc</sub> curves merge, called the irreversible temperature ( $T_{irr}$ ), corresponds to the temperature above which all particles are in a superparamagnetic state. The difference in magnetization between M<sub>fc</sub> and M<sub>zfc</sub> curves, below  $T_{irr}$  can thus be

explained by the acquisition of a remanent magnetization by the particles while blocking in an external field [Dormann *et al.*, 1997]. In addition, low-temperature alternating field magnetic susceptibility values were measured from 10 to 300 K. The in-phase ( $\chi'$ ) and quadrature ( $\chi''$ ) components of the magnetic susceptibility were acquired in a  $10^{-4}$  T driving field oscillating at frequencies of 10 and 100 Hz (Figure 1D). The temperature evolution of  $\chi'$  is characterized by a peak at about 60 K, with a slight frequency dependency, highlighted by the presence of a peak in  $\chi''$  [Néel, 1949]. This observation is consistent with the thermal unblocking of superparamagnetic particles, and has been observed in previous studies of well characterized synthetic 6-line ferrihydrite samples [Berquo *et al.*, 2007; Guyodo *et al.*, 2006]. Considering the transmission electron microscopy based particle sizes reported at different temperatures for our synthesis procedure [Erbs *et al.*, 2008] and a sample synthesis temperature of 52°C, the average particle size of our Fh sample is estimated to be around 4.4 nm. In view of the blocking temperatures reported by Guyodo *et al.* [2006] and associated average particle sizes,  $T_b$  determined from data in Figure 1C and D of our synthetic Fh sample is compatible with a particle size of 4.4 nm. Overall, the low temperature magnetic data acquired on our Fh sample are characteristic of genuine, standard 6-line ferrihydrite nanoparticles.

### **XMCD measurements**

Iron  $L_{2,3}$  and K edge XMCD measurements were performed following well established experimental procedures for the SIM beamline at SLS [Carvallo *et al.*, 2008] and for the ID12 beamline at ESRF [Carvallo *et al.*, 2010; Rogalev *et al.*, 2001]. XMCD spectra were obtained by taking the direct difference between two x-ray absorption spectra (XAS) successively collected with left- then right-circularly polarized x-rays in the presence of a magnetic field. In this study, all XMCD spectra were measured after cooling the samples to below 15 K, well below  $T_b$  of our Fh sample, in order to perform measurements on particles in a stable



magnetic state. Furthermore, an external magnetic field of  $\pm 6$  T was applied to maximize the magnetic signal carried by ferrihydrite. At ESRF, measurements were acquired on 10 mm diameter pellets made from the initially powdered samples, while at SLS, samples were obtained by drop-casting on copper plates. The signal to noise ratio was improved by calculating average XMCD based on multiple individual measurements. In order to make sure that the measured XMCD spectra are free of artifacts, we verified that spectra obtained in -6 T were opposite to those obtained in +6 T.

XMCD results are shown in Figure 2, where black lines represent ferrihydrite and gray lines represent maghemite. Figures 2A and 2B represent average isotropic XAS acquired at the iron K and  $L_{2,3}$  edges, respectively. Isotropic XAS were normalized to 1 well above the edge for K-edge measurements, and normalized to 1 at the peak of the  $L_3$  edge for  $L_{2,3}$  edge measurements. The resulting isotropic XAS are similar to previously published data [Brice-Profeta *et al.*, 2005; Carvallo *et al.*, 2008, 2010; Guyodo *et al.*, 2006; Maillot *et al.*, 2011; Zhao *et al.*, 1994]. In Figures 2C and 2D, the overall intensity of the ferrihydrite XMCD features is about an order of magnitude smaller than that of maghemite. This result is consistent with the difference in spontaneous magnetization between the two minerals (maghemite saturation magnetization is about  $80 \text{ Am}^2/\text{kg}$  [Hunt *et al.*, 1995], while the magnetization at 6 T of our ferrihydrite sample is about  $10 \text{ Am}^2/\text{kg}$ , Figure 1). This again attests that the measured XMCD spectra reflect efficiently the bulk magnetic properties of our sample. At K-edge, previous studies have shown that maghemite pre-edge XMCD features (labeled A and B on Figure 2C) are due to Fe(III) located at tetrahedral sites, because octahedral sites provide only small effects [Carvallo *et al.*, 2010; Sikora *et al.*, 2010]. In Figure 2C, the shape and energy positions of these features are similar to previously published data [Carvallo *et al.*, 2010]. Theoretical calculations [Sikora *et al.*, 2010] have shown that the

216 A and B features could be fully interpreted as originating from Fe(III) on tetrahedral sites.  
 217 Strikingly, these features are also clearly present in the XMCD data of our Fh sample. This  
 218 observation provides unambiguous support in favor of the most recent EXAFS analysis of 6-  
 219 line ferrihydrite [Maillot *et al.*, 2011], which suggests the presence of a significant amount of  
 220 tetrahedral iron in Fh. At the  $L_{2,3}$  edge, maghemite XMCD features are also similar to  
 221 previously published data [Brice-Profeta *et al.*, 2005; Carvallo *et al.*, 2008]. At the  $L_3$ -edge,  
 222 according to previous multiplet theory calculations [Brice-Profeta *et al.*, 2005], the positive  
 223 peak labeled as C on Figure 2D is due to tetrahedral iron, while the two negative peaks  
 224 labeled as D1 and D2 in Figure 2D are due to octahedral iron. At the  $L_2$ -edge, the peaks  
 225 remain essentially positive, with slight variations due to the competing influence of the  
 226 tetrahedral and octahedral sites. Again, as observed at K-edge, the shape of the Fh XMCD  
 227 spectrum is similar to that of Mh1. Provided the presence of a well-developed positive peak  
 228 at the  $L_3$ -edge in Fh, and provided that the peaks observed at the  $L_3$  and  $L_2$  edges of Fh are  
 229 located at the same energies as in Mh1, our data confirm the presence of a significant amount  
 230 of tetrahedral Fe(III) in Fh. The ratio of the C to D2 peaks in Fh is, however, lower than in  
 231 maghemite, which suggests a lower amount of tetrahedral iron. We used the Ligand Field  
 232 Multiplet model [de Groot and Kotani, 2008; Thole *et al.*, 1985] to calculate the  $[Fe_{Td}]/([Fe_{Td}]$   
 233  $+ [Fe_{Oh}])$  tetrahedral vs octahedral contributions to the XMCD for Mh1 and Fh, using our well  
 234 established previous calculation for maghemite nanoparticles and the same ligand field  
 235 parameters [Brice-Profeta *et al.*, 2005]. An illustration of these calculations is shown in  
 236 Figure 3A, where several model XMCD spectra were calculated for various tetrahedral  
 237 contributions. It is clear from Figure 3A that the C and D2 peaks have the greatest sensitivity  
 238 to the tetrahedral versus octahedral contributions. Using these calculations, we confirm that  
 239 Mh contains  $37.5 \pm 3\%$  of tetrahedral iron as expected for stoichiometric maghemite (Figure  
 240 3B). Based on these parameters, calculation of the Fh XMCD spectrum indicates that 6-line

Fh contains  $28 \pm 3\%$  of tetrahedral iron (Figure 3B). One should keep in mind, however, that maghemite and Fh do not share exactly the same magnetic characteristics. Maghemite is ferrimagnetic with a magnetic moment that is well saturated below the applied field of 6 T, while Fh is not saturated in 6 T and is currently thought of as an imperfect antiferromagnetic mineral with non-compensated moments. The magnetization carried by the uncompensated moments has been shown to be size dependent [Guyodo *et al.*, 2006]. As a consequence, to some extent, the XMCD signal may also be size dependent. It is also possible that the value of 28% for tetrahedral iron found here depends on whether the distribution of the non-compensated moments is homogenous between octahedral and tetrahedral sites. Distinguishing between core and surface contributions may be difficult. At  $L_{2,3}$  edge, the TEY detection mode is sensitive to the top 10 nm of the sample. Since Fh nanoparticles are less than 5 nm, the whole volume of the nanocrystallites is probed, and surface and core both contribute to the XMCD signal. At K-edge, the penetration depth of the FY detection mode is larger than 1000 nm, probing large clusters of nanoparticles. The fact that XMCD in the pre-edge region from Fh and Mh have similar shape is a confirmation that the similarities observed at Fe  $L_{2,3}$  edge are indeed observed with a larger penetration depth at Fe K-edge.

## **Conclusions**

Results from the first XMCD investigation of a synthetic sample of 6-line ferrihydrite at both K and  $L_{2,3}$  edges of iron provide strong evidence for the presence of a significant amount of tetrahedrally coordinated Fe(III) in the mineral structure. With respect to the ongoing debate about the mineral structure of ferrihydrite, our results support recent studies that advocate the presence of 20 to 30% of tetrahedral iron. Although a detailed structural model remains to be established, our findings represent the first direct experimental evidence for the presence of tetrahedral Fe(III) in ferrihydrite. This direct evidence is confirmed by Ligand Field Multiplet

calculations. Moreover, we find an antiferromagnetic coupling between the sublattices of Fe<sub>Td</sub> sites and Fe<sub>Oh</sub> sites, with the Fe<sub>Oh</sub> sublattice parallel to the external magnetic field. Since XMCD at K and L<sub>2,3</sub> edges is almost insensitive to the iron environment beyond the coordination shell, we cannot propose a definite crystallographic structure from our measurements. Nonetheless, our present results place a strong constraint on future structural models based on crystallographic experiments. In addition, further XMCD measurements should be performed on other samples to test the possible influence of crystallinity (e.g., 2-line versus 6-line) on the magnetic structure of ferrihydrite.

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## **Figure captions**

**Figure 1:** (A) X-ray diffraction spectra of the three samples: ferrihydrite (Fh), maghemite (Mh1 and Mh2). Peaks labeled H correspond to halite (NaCl). (B) Magnetic hysteresis loop of sample Fh between -10 and +10 T, at 5 K. (C) Field cooled (Mfc) and zero field cooled (Mzfc) induced magnetizations obtained with a 5 mT field. (D) Low-temperature in-phase ( $\chi'$ ) and quadrature ( $\chi''$ ) alternating field magnetic susceptibility with driving field frequencies of 10 and 100 Hz.

**Figure 2:** (A) and (B) XAS normalized spectra of ferrihydrite and maghemite at the iron K and  $L_{2,3}$  edges, respectively. (C) and (D) Corresponding XMCD spectra of ferrihydrite and maghemite. Two-sigma standard errors are represented as gray shading in (C) and are smaller than the line thickness in (D).

**Figure 3:** (A) Illustration of the effect of varying the amount of tetrahedral Fe(III) on the shape of calculated XMCD spectra: theoretical cross-sections are expressed in  $\text{\AA}^2$ . (B) Calculated XMCD spectra with 28% and 37.5% of tetrahedral Fe(III) (black solid line), to be compared to the experimental XMCD data (gray dotted line) for ferrihydrite and maghemite, respectively: experimental cross-sections are expressed as a percentage of the  $L_3$  maximum for the isotropic XAS, i.e.,  $(S_{\text{Left}} + S_{\text{Right}})/2$ .





