



Co-precipitation in aqueous solution synthesis of magnetite nanoparticles using iron(III) salts as precursors



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KEYWORDS

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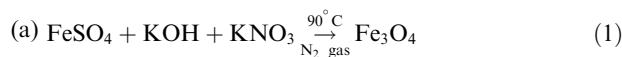
Abstract An innovative quantitative synthetic method for preparing magnetite nanoparticles was achieved by co-precipitation in aqueous solution using only one single iron(III) salt as a precursor. A 2 Fe(III):1 Fe(II) mole ratio was first attained in solution by reducing iron(III) using KI solution, followed by filtering the iodine formed and hydrolyzing the filtrate by 25% ammonium hydroxide solution at pH 9–11. A high selectivity and atom economy percents were achieved indicating that the method is environmentally benign and green. The as-synthesized nanoparticles were characterized by fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM), field emission transmission electron microscopy (FETEM), selected area electron diffraction (SAED), and ^{57}Fe Mössbauer spectroscopy. Magnetite nanocrystals (d: 7.84 ± 0.05 nm) and nanorods (d: 6.3 ± 0.2 nm; l: 46.2 ± 0.9) formation was evident.

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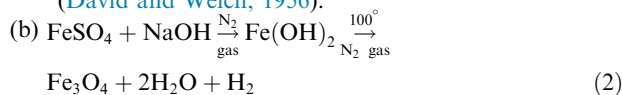
1. Introduction

Synthesis, characterization and applications of iron oxide nanocrystals have received tremendous attention in recent years due to their potentials for information storage devices, rotary shaft sealing, position sensing (Raj and Moskowitz, 1990), as well as medical and pharmaceutical applications (Xie et al., 2008). Several methods are known in the art for

the synthesis of magnetite, Fe_3O_4 . Cornwell and Schwertmann (Cornwell and Schwertmann, 2003) have reported several synthetic methods all of which require more than one iron component as precursors, several chemical reagents, inert atmosphere, special apparatus and/or restricting conditions. Exemplary methods are shown as follows:



(David and Welch, 1956).



(produces complicating side effect) (Schikorr, 1929).

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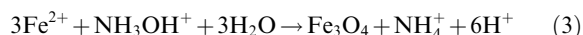
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(c) Reduction of hematite at 400 °C in an atmosphere of 5% H₂/95% Ar, saturated with water vapour free of O₂ (Regazzoni et al., 1981).

(d) Reaction of a 1:2 Fe(II)/Fe(III) solution, under alkaline conditions at 80 °C under N₂ (Regazzoni et al., 1981).

(e) Reaction at 85 °C of Fe(II) ammonium solution (buffered to pH 7 to 8 with sodium acetate) with hydroxylamine sulfate; the suspension is held under N₂ gas (Ardizzone and Formaro, 1983), as shown thus



(f) Reductive transformation in a sealed ampoule of an akaganeite suspension in the presence of hydrazine at pH 9.5 to 11.5 and 100 °C (Blesa and Maroto, 1986).

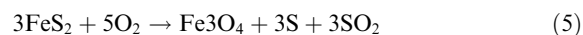


(g) Decomposition of an alkaline (0.2–0.4 MOH) solution of Fe(III) NTA at 217 °C in an autoclave (Booy and Swaddle, 1978).

(h) Heating of iron hydroxide acetate at 200–260 °C under N₂ (Pinheiro et al., 1987).

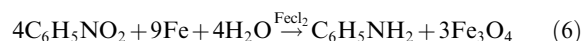
(i) Boiling a mixture of Fe(II) sulfate and bispyridoxylidene hydrazine phthalazine for 10 min at pH 7 (Sarel et al., 1989).

(j) Thermal decomposition of Fe(II) sulfide in air at 500 °C, which is environmentally unfriendly (Robl, 1958).



(k) Holding a solution of Fe(III) acetylacetonate in 1-propanol under N₂ in an autoclave at 300 °C for several hours (Kominami et al., 1999).

(l) Reduction of nitrobenzene to aniline produces Fe₃O₄ (Laux, 1925) as shown thus:



Further, several Fe₃O₄ synthetic methods were patented (Michael et al., 2004; Shen, 2002; Yoshito et al., 1984; Tomio and Horoyuki, 1999; Shouheng, 2002; Maurice et al., 1978; Naoyoshi and Kenzo, 2000).

The most popular methods for the synthesis of the spinel structured Fe₃O₄ include co-precipitation in aqueous solution by adding hydroxides into iron salt solutions (Hui et al., 2008; Fried et al., 2001) and the thermal decomposition of iron organometallic compounds in high boiling organic solutions in the presence of stabilizers (Sun and Zeng, 2002; Xu et al., 2010).

Recently, Xu et al. (2010) reported on the organic phase synthesis of mono dispersed iron oxide nano crystals using iron chloride as a precursor.

In this paper, a report was made on an innovative invention (Khalil, 2012) that relates to a process of preparing magnetite nanocrystals by the co-precipitation method using iron(III) chloride or nitrate salts as precursors. The objective of this invention was to provide a process of preparing magnetite (Fe₃O₄) and derivatives thereof, not reported herein, which overcomes the drawbacks of the prior art, especially a process which only requires one iron compound as the starting precursor, a limited number of additional chemical reagents, and a process which can be carried out under simple reaction

conditions, preferably at room temperature, with easy work-up of the product obtained.

2. Experimental

2.1. Starting material

Iron chlorides (FeCl₃ and FeCl₃·6H₂O) were purchased from WINLAB, Leicestershire, England. Iron nitrate (Fe(NO₃)₃·9H₂O) sodium hydroxide (NaOH) and 25% ammonia solution were all purchased from BDH, Poole, England. And potassium iodide (KI) and polyvinyl alcohol (PVA 72000) were purchased from MERCK, Darmstadt, F.R. Germany.

2.2. Characterization

The FTIR spectrum was recorded on a Shimadzu FTIR-8400S, Prestige-21 spectrophotometer in a KBr matrix. Powder X-ray diffraction (XRD) pattern was obtained with an Ultima IV X-ray diffractometer using copper-monochromatized Cu Kα 1 radiation under the acceleration voltage of 40 kV and a current of 40 mA. The morphology of the Fe₃O₄ nanocrystals was examined by a JEOL JSM-6380 LA scanning electron microscope and a JEOL, TEM-2100F transmission electron microscope with an acceleration voltage of 200 kV. ⁵⁷Fe Mössbauer spectra were recorded in the Institute des Molecules et Matériaux du Mans (IMMM), Université du Maine, France.

2.3. Synthesis of magnetite nanoparticles

The work-up consists of mixing iron(III) salt solution with potassium iodide aqueous solution in a 3:1 mol ratio, filtering out the iodine formed, hydrolyzing the filtrate with either sodium hydroxide or ammonia solution, filtering the black magnetite precipitate, washing with water and drying at 250 °C.

An exemplary experiment is carried out as follows:

19.46 g (0.119 mol) of anhydrous FeCl₃ was completely dissolved in 150 ml distilled water to prepare aqueous solution A. Further, 6.584 g (0.0396 mol) of potassium iodide was dissolved in 50.0 ml of distilled water to prepare aqueous solution B. Solutions A and B were then mixed together at room temperature, stirred and allowed to reach equilibrium for one hour. The precipitate of iodine was filtered out, washed with distilled water, dried at 100 °C and weighed (yield: 5.076 g, 86.6%). The washing was added to the filtrate. The whole volume of filtrate was then hydrolyzed using 25% ammonia solution which was added drop-wise with continuous stirring until complete precipitation of the black magnetite was achieved (pH 9–11). The set up was then left to settle, filtered, washed with distilled water, dried at 250 °C and weighed (yield: 9.2 g, 99.0%).

The same procedure was repeated using FeCl₃·6H₂O as a precursor. 27.03 g FeCl₃·6H₂O dissolved in 150.0 ml distilled water was reacted with 5.533 g (0.033 mol) KI aqueous solution. Iodine yield was 3.15 g, 75.53%. Magnetite was precipitated from three 50.0 ml portions of the filtrate. The average yield was 1.40 g, 91.61%.

The yield of magnetite from Fe(NO₃)₃·9H₂O precursor was low (52.8%) when a 3Fe(III): 1.0 KI mole ratio was used.

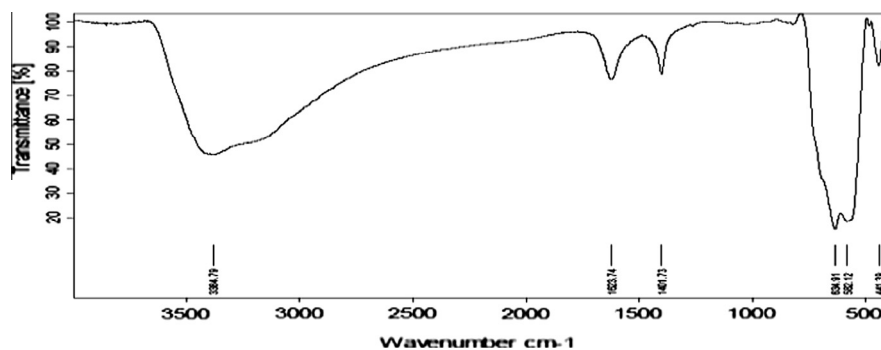


Figure 1 FTIR spectrum of the as-synthesized magnetite.

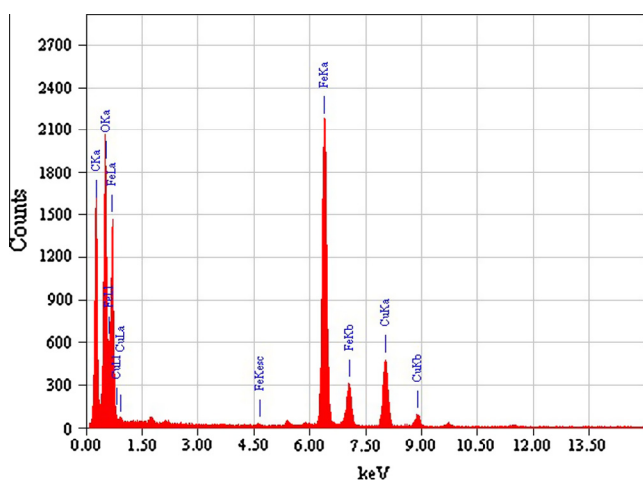


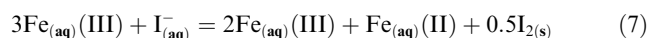
Figure 2 EDS pattern of the as-synthesized magnetite.

Increasing the ratio to 1:1.325 yielded a 97.0% I_2 and a 96.85% Fe_3O_4 .

3. Results and discussion

Instead of using two iron precursors, that is Fe(III) and Fe(II) mixed in a 2:1 mol ratio for the preparation of magnetite, one

can start with only an aqueous iron(III) salt solution and reduce it by potassium iodide to maintain the appropriate mole ratio according to Eq. (7):



Thereafter, filtering out the iodine precipitate and then hydrolyzing the filtrate by 25% ammonium or sodium hydroxide solution at pH 9–11 were used to obtain black magnetite nanoparticles. The percentage yield of magnetite and iodine was 99% and 86%, respectively.

This innovative method for the preparation of magnetite is economical and green, achieving a high selectivity and atom economy percents (Lancaster, 2002). Eqs. (8) and (9) imply that both magnetite and iodine are desired products.

$$\%Selectivity = 100 \times (9.2 + 5.076)/(19.46 + 6.584) = 54.78\% \quad (8)$$

$$\%Atom \text{ economy} = 100 \times (485.35 + 126.9)/(487.05 + 165.8) = 93.78\% \quad (9)$$

The FTIR spectrum of the as-synthesized magnetite from anhydrous $FeCl_3$ (Fig. 1) exhibited vibrational bands at 634 sh., 582 s, 397 m cm^{-1} characteristic of magnetite (Cornwell and Schwertmann, 2003; Zheng et al., 2011; Liese, 1967). The intense band at 582 cm^{-1} could be assigned to the IR active T_{1u} mode corresponding to the vibration of the

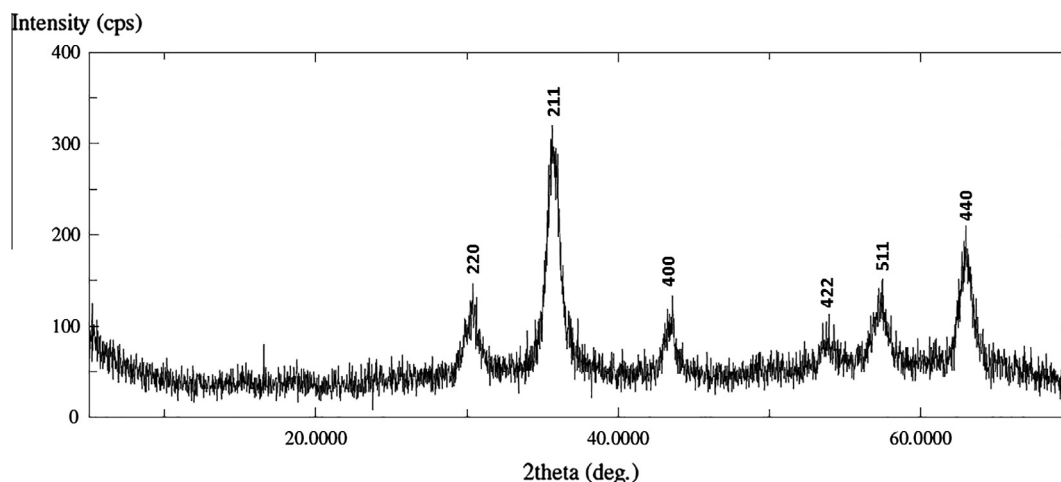


Figure 3 XRD pattern of the as-synthesized magnetite.

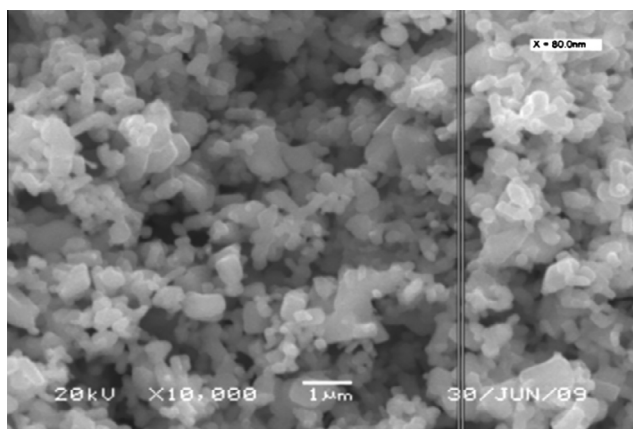


Figure 4 SEM image of the as-synthesized magnetite.

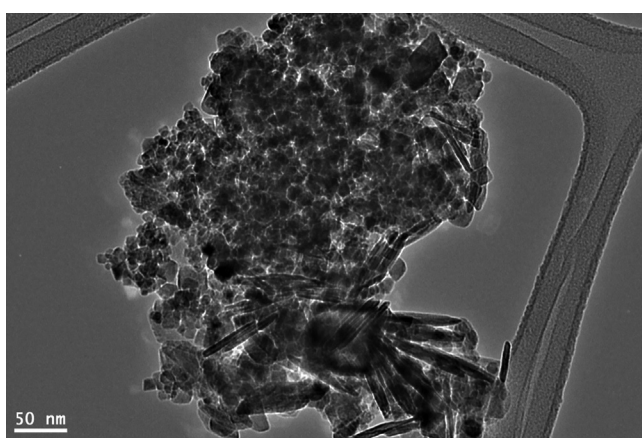


Figure 5 TEM image of the as-synthesized magnetite.

$\text{Fe}^{2+}-\text{O}^{2-}$ functional group. The splitting-up peak at 634 cm^{-1} is due to the symmetry degeneration on octahedral B sites (Zheng et al., 2011). Rowan and Patterson (Rowan and Patterson, 2009) have reported that for monoclinic unit cell at low temperature, the IR modes in the $\text{Fe}^{2+}-\text{O}^{2-}$ stretching vibrational band would be induced as obvious split pairs for fields along the x and y directions.

The EDS intensity peaks (Fig. 2) show the exact iron percent in Fe_3O_4 . The Cu signals were from the Cu grid. No other signal was detected within the detection limits of EDS which confirms the purity of the Fe_3O_4 nanoparticles.

The crystallinity of the magnetite sample was investigated by XRD as shown in Fig. 3. The results show that the sample has six peaks at 2θ of 30.36° , 35.74° , 43.52° , 53.95° , 57.34° and 63.0° representing the corresponding indices of (220), (311), (400), (422), (511), and (440) respectively (Cornwell and Schwertmann, 2003; Xu et al., 2010).

The crystal system is cubic with Z value of 8.0, $a = b = c = 8.3199\text{ \AA}$, $\alpha = \beta = \gamma = 90^\circ$ belonging to space group Fd-3m.

A typical scanning electron microscopic (SEM) image of the as-synthesized iron oxide nanoparticles is shown in Fig. 4. It is evident from the picture that the particles are in a nano scale.

TEM image (Fig. 5) of the synthesized magnetite indicates the formation of nanocubes and nanorods composite.

The selected area electron diffraction (SAED) pattern of the as-synthesized iron oxide is shown in Fig. 6(a). The high resolution TEM image of a single iron oxide cube (Fig. 6b) shows lattice fringes with an interfringe distance of 0.292 nm , which is close to the interplane distance (220) of the planes in the cubic spinel structured iron oxide (Xu et al., 2010).

Information of the mean size and standard deviation (SD) was calculated from measurements of the nano cubes and nanorods in random fields of view and presented in Fig. 7. The mean \pm SD of the nanocubes was $7.8 \pm 0.05\text{ nm}$ while the mean \pm SD of the nanorods was $6.3 \pm 0.2\text{ nm}$ in diameter and $46.2 \pm 0.9\text{ nm}$ in length.

Liquid nitrogen temperature (77 K) and room temperature (300 K) ^{57}Fe Mössbauer spectra of one magnetite-loaded PVA dry hydrogel sample are presented in Fig. 8(a) and (b). The 77 K recorded spectrum, Fig. 8(a), is similar to that of an assembly of 8–10-nm noninteracting magnetite particles published by Morup et al. (1980) and Szabó et al. (2000). The RT ^{57}Fe Mössbauer spectrum consists of two sextets with isomer shifts of 0.15 mm/s and a hyperfine field of 48.6 T for Fe^{3+} in the A sites and 0.56 mm/s and a hyperfine field of 45.7 T for the $\text{Fe}^{2.5+}$ average valence on the B sites (Dzėsi et al., 2008). A quadrupole splitting of 0.00 and -0.01 mm/s is indicative of

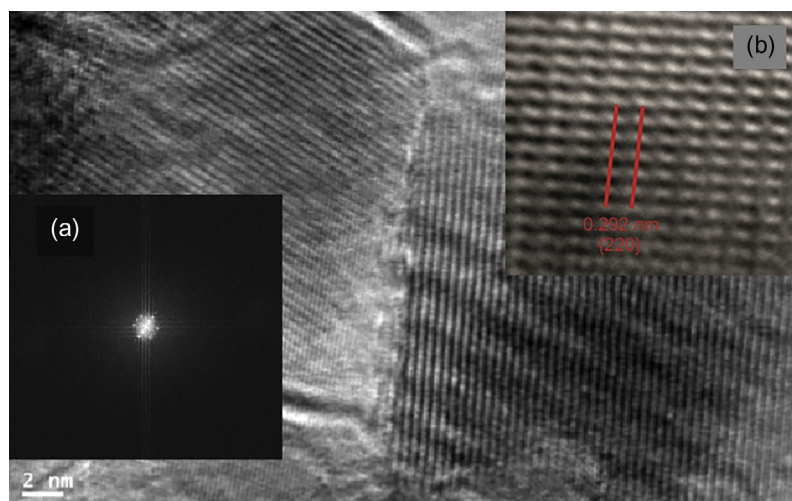


Figure 6 HRTEM image of a single magnetite cube; (a) SAED pattern and (b) Lattice fringes.

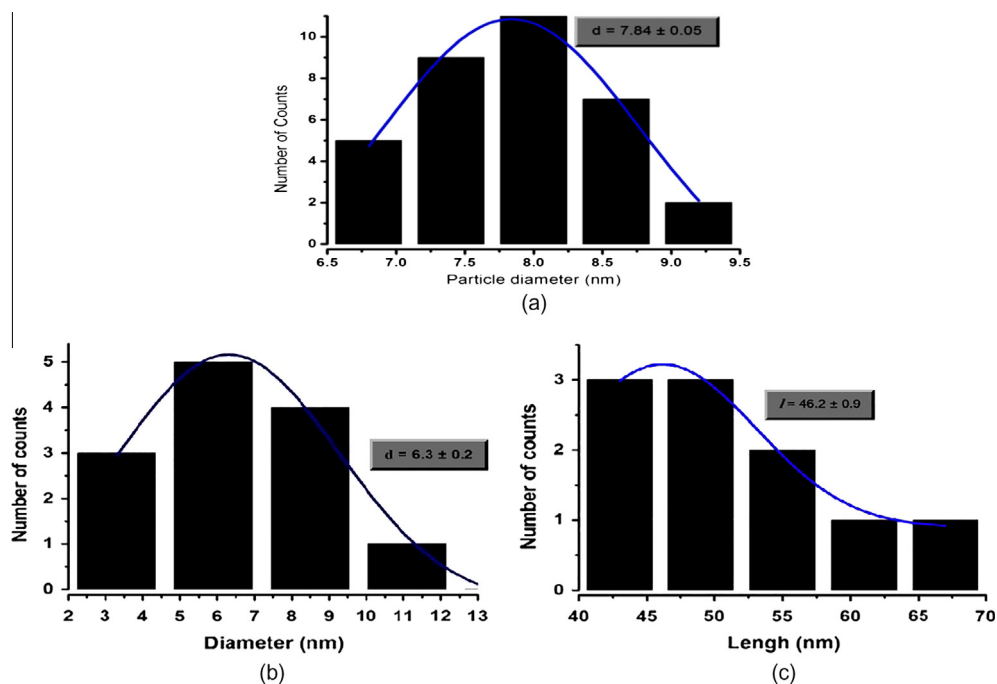


Figure 7 Mean size and standard deviation of: (a) Fe₃O₄ nano cubes; (b and c) Fe₃O₄ nano rod.

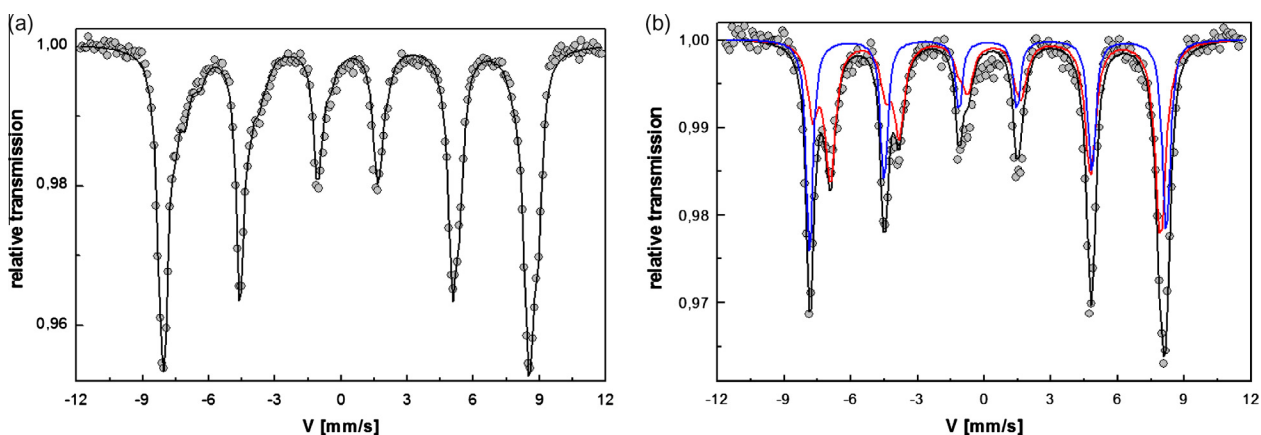


Figure 8 Mössbauer spectra of a disk-shaped dried ferrogel at 77 K (a) and 300 K (b).

cubic symmetry. The absence of a paramagnetic component indicates that the transition to paramagnet occurs above 300 K.

Detailed ⁵⁷Fe Mössbauer effect study will be conducted and published elsewhere.

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