Characterization of Horse-Spleen Ferritin as a Magnetic core-shell Nanoparticle

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By

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CERTIFICATE

This is to certify that the thesis entitled "**Characterization of Horse spleen Ferritin as a Magnetic core-shell Nanoparticle**" submitted by Ms. Ravneet Kaur (Roll No: 30704015) of M. Sc. (Physics), Thapar University, Patiala, was carried out by her under supervisions of Dr. S. D. Tiwari and Ms. Loveleen K. Brar. She has not submitted this material for credit towards any other degree at this or any other university.

Thesis work carried out from 7.1.2009 to 14.7.2009.

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DECLARATION

I hereby declare that the thesis entitled **"Characterization of Horse spleen Ferritin as a Magnetic core-shell Nanoparticle"** is the original work carried out by me under the joint supervision of Dr. S. D. Tiwari and Ms. Loveleen K. Brar. The matter embodied in this thesis has not been submitted anywhere else for the award of any degree.

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RAVNEET KAUR

Abstract

Horse spleen Ferritin is characterized by X-ray diffraction, transmission electron microscope (bright field imaging and electron diffraction), differential thermal analysis, thermogravimetric analysis and vibrating sample magnetometer. Ferritin is found to be an almost spherical nanoparticle having size of about 8 nm and amorphous in nature. The core of the Ferritin decomposes at about 800 K. Ferritin is found to be antiferromagnetic at room temperature and its magnetic susceptibility at room temperature is about 6.0×10^{-4} emu / g Oe.

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CHAPTER 1
INTRODUCTION

Work on magnetic nanoparticles is of great interest for scientists from a wide range of disciplines. The properties of these nanoparticles depend largely on their chemical structure and synthesis method. The nanoparticles need to be functionalized for many applications. In such cases the particles have core-shell morphology. The effect of the shell on the magnetic properties of the particle also needs to be studied. Ferritin is the primary protein for iron storage in most living organisms [1]. It consists of an iron oxyhydroxide core about 7 nm in size. This core is surrounded by a protein shell of about 12 nm in diameter.

1.1 Magnetism and its Origin

Magnetic flux density B due to applied magnetic field H in vacuum are related as [2-4]

$$\boldsymbol{B} = \mu_0 \mathbf{H}$$

where, μ_0 is called permeability of the free space.

If magnetic field is applied to a medium, magnetic induction in the solid is given by

$$\boldsymbol{B} = \mu \mathbf{H}$$

Where, μ is the permeability of the medium through which magnetic lines of force pass.

The ratio μ/μ_0 is called the relative permeability, μ_r of the medium.

The magnetic induction in a solid is also defined by

$$\boldsymbol{B} = \mu_0 (\mathbf{H} + \mathbf{M})$$

Where, magnetization ***M*** is defined as the magnetic moment per unit volume.

The magnetic susceptibility per unit volume is defined as

$$\chi = \frac{M}{H}$$

Where, ***H*** is the magnetic field intensity.

The orbital motion and spin of electron in an atom is responsible for its magnetic moment. The orbital magnetic moment μ_{orb} of an electron is related to its orbital angular momentum L by relation

$$\mu_{orb} = -\frac{e}{2m_e} L$$

Where, e is magnitude of charge on electron and m_e is mass of the electron.

The spin magnetic moment μ_{spin} of an electron is related to its spin angular momentum S by relation

$$\mu_{spin} = -\frac{e}{m_e} S$$

The net magnetic moment of an electron is the vector sum of the orbital and spin magnetic moments. In a closed shell within an atom this vector sum is zero. So in an atom only the unpaired electrons in partially filled shells contribute for the magnetic moment of the atom.

Based on behavior of the materials in external applied magnetic field the materials can be classified into following categories [2-4].

Diamagnetism

Diamagnetic materials are composed of atoms which have no net magnetic moments. Diamagnetic materials have negative and very small (10^{-6}) value of magnetic susceptibility. So, these materials oppose the applied external magnetic field, and are therefore repelled by the magnetic field. The magnetic susceptibility of diamagnetic materials is independent of temperature. Examples of diamagnetic materials are organic materials, covalent solids etc.

Paramagnetism

In paramagnetic materials some of the atoms or ions in the material have a net magnetic moment due to unpaired electrons in partially filled orbitals. The orientation

of these magnetic moments is random. So in the absence of applied magnetic field, these materials have no net magnetic moment. When an external magnetic field is applied, these magnetic moments tend to align themselves in the same direction as the applied field, thus reinforcing it. The susceptibility for these materials is positive and small (10^{-5}). The susceptibility of paramagnetic materials depends on temperature.

Ferromagnetism

Ferromagnetic materials exhibit parallel alignment of neighboring magnetic moments resulting in large net magnetization even in the absence of a magnetic field. So these materials have very large and positive value of susceptibility. Above a critical temperature, known as Curie temperature the ferromagnetic materials become paramagnetic. The elements Fe, Ni, and Co and many of their alloys are typical ferromagnetic materials.

Antiferromagnetism

Antiferromagnetic materials posses a magnetic ordering in which the magnetic moments of alternating atoms in the crystal are aligned in opposite directions. Antiferromagnetic materials have a small but positive susceptibility. They don't possess any magnetic moment in absence of magnetic field. Antiferromagnetism occurs below a critical temperature called Néel temperature. Above Néel temperature the antiferromagnetic materials become paramagnetic.

Ferrimagnetism

Ferrimagnetic materials exhibit magnetic behavior similar to that of ferromagnetic materials below critical temperature. In these materials, like antiferromagnets, neighboring pairs of electron spins point in opposite directions. But the magnitude of the moments is not the same and hence they do not cancel out.

1.2 Magnetic Nanoparticles

Nanoparticles of a given material can be prepared by reducing all its three dimensions to nanometer range. Studies of magnetic nanoparticles are of great interest for scientists and engineers mainly because of its technological applications.

Small particles of magnetic material have a large magnetic moment per unit mass and behave like a paramagnetic moments with a fast response to applied external magnetic fields. Such system has negligible remanence magnetization and coercive field. This is known as superparamagnetism [5]. In other words, the superparamagnetism is a phenomenon by which small particles of magnetic materials may exhibit a behavior similar to paramagnetism at temperature below the curie or Néel temperature.

1.3 Core-shell Nanoparticles

These are structured nanoparticles that comprise a core of one material and a coating shell of another material. The composition of the core and shell can be varied to give a wide range of different properties, a few of which are indicated in the Fig. 1.1.

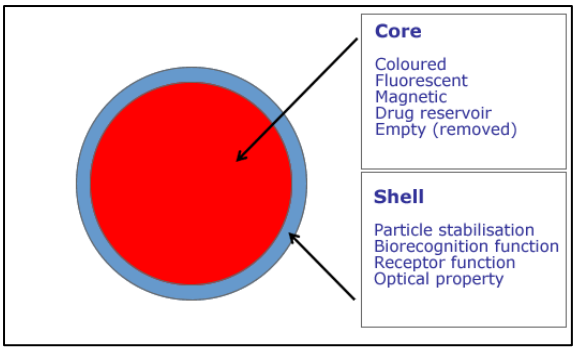

Fig.1.1: Schematic of a core-shell particle. [6]

1.4 Ferritin

Ferritin is an iron storage protein found in almost all biological systems. Each Ferritin molecule has a spherical protein shell which can store 2000 to 4500 iron atoms as Fe(III). Ferritin protein has 24 peptide subunits assembled into a hollow spherical shell of diameter about 60 to 80 Å. Walls of the shell are about 20 Å thick. The molecular weight of Ferritin (i.e., with all 24 subunits combined) is 474,000 g / mol. There are small holes, called channels, in the shell through which certain ions or molecules can travel. The channels in the sphere are formed at the intersections of three or four peptide subunits [7]. These channels are critical for Ferritin's ability to release iron in a controlled fashion (Fig 1.3).

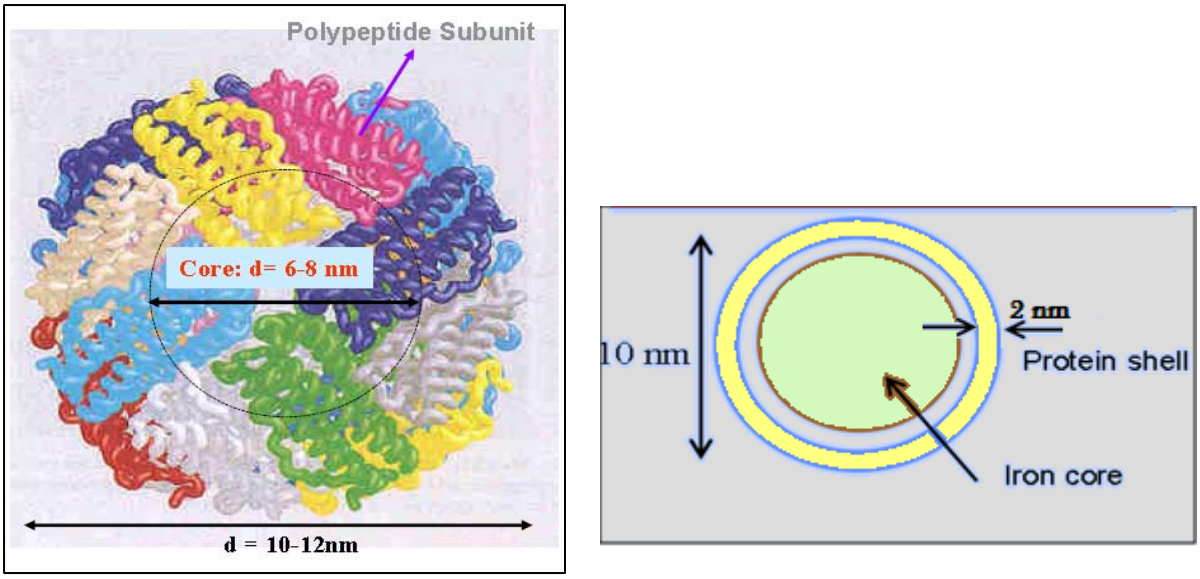

Fig.1.2: (a) 3-D representation of Ferritin molecule [8], (b) schematic of a core-shell of Ferritin molecule.

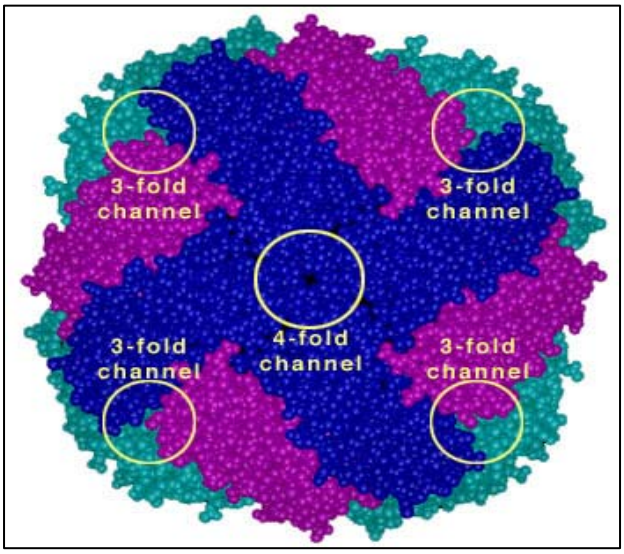

Fig. 1.3: 3-fold and 4-fold channels in Ferritin molecule. [7]

1.5 Core of Ferritin

The shell of Ferritin with an empty core is called Apoferritin and the iron core is called Holoferritin. The iron in the Ferritin core is stored as Fe(III) in a crystalline solid that has the chemical formula $[FeO(OH)]_8$ $[FeO(H_2PO_4)]$ with a structure quite similar to the mineral ferrihydrite [9].

The soluble Fe(II) enters the protein shell and goes through the following chemical processes to form the iron core [9].

$$2Fe^{2+} + O_2 + 6H_2O \Longrightarrow 2Fe(OH)_3 + H_2O_2 + 4H^+$$

$$4Fe^{2+} + O_2 + 10H_2O \Longrightarrow 4Fe(OH)_3 + 8H^+$$

When Ferritin releases iron, electrons are transferred through the protein shell to reduce the Fe(III) in the mineral lattice to Fe(II), rendering the iron soluble and it can be released from Ferritin.

1.6 Horse spleen Ferritin

Horse spleen Ferritin is the most widely studied Ferritin molecule. It is mostly (85%) composed of identical subunits [9] and its structure has been completely characterized by single crystal X-Ray diffraction. Within a Ferritin molecule the Holoferritin core and the Apoferritin shell has the same morphology as a core-shell nanoparticle consisting of an antiferromagnetic compound core and organic shell.

In this thesis the horse spleen Ferritin is characterized as a magnetic nanoparticle using different techniques such as x-ray diffraction, transmission electron microscopy, thermogravimetric analysis, differential thermal analysis and vibrating sample magnetometer.

1.7 Organization of Thesis

The organization of the thesis is as follows.

Chapter 1 provides the introduction to the area.

Chapter 2 provides the details of experimental techniques used for the characterization of Ferritin.

Chapter 3 provides the detailed structural analysis of Ferritin.

Chapter 4 provides the detailed thermal analysis of Ferritin.

Chapter 5 provides the magnetization measurements of Ferritin.

Chapter 6 provides conclusions of the thesis and scope for future work.

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CHAPTER 2

EXPERIMENTAL DETAILS

2.1 Structural Characterization

Structural characterization of nanoparticles includes the determination of its morphology, size and crystallinity. In the present study the structural characterization of Ferritin is done by X-ray diffraction, Transmission Electron Microscope and Electron diffraction.

2.1.1 X-ray Diffraction

X-ray diffraction provides information about the relative arrangements of atoms or ions inside a crystalline material. Crystal structure can be studied through the diffraction of photons, neutrons and electrons. The diffraction depends upon crystal structure and on the wavelength of radiation used [1]. When wavelength of the falling radiation is smaller than or comparable to the lattice constant, a diffracted beam may be found. Bragg gives the simple explanation of diffraction of incident X-ray beam from a crystal.

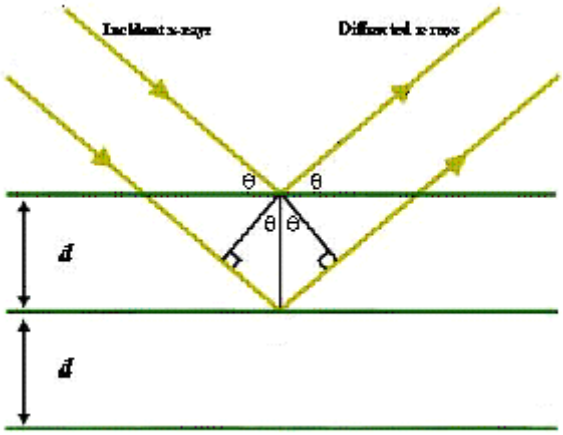

Fig. 2.1 Schematic of Bragg's law.

According to Bragg the incident waves are reflected from parallel planes of atoms in crystal, with each plane reflecting only a very small fraction of the radiation. In this refection the angle of incidence is equal to angle of reflection. Let a parallel beam of X-rays is incident on a set of parallel planes of atoms in the crystal as shown in Fig 2.1. The path difference for rays reflected from adjacent plane is $2d\sin\theta$, where θ is measured from plane. Diffracted waves from successive planes can interfere with each other and the resultant intensity distribution is strongly modulated by this interaction. This lead to a relationship between the wavelength λ of X-rays, the spacing d between lattice plane and angle of incidence θ. Intense diffracted beams are obtained when the reflections from parallel planes of atoms interfere constructively. The condition for this is given by Bragg's law

$$2d\sin\theta = n\lambda \qquad (1)$$

where, n is an integer.

If the atoms are arranged in a periodic fashion, as in crystals, the diffracted waves will consist of sharp interference maxima. The positions of the peaks in the X-ray diffraction pattern are used to identify the structure of the material.

2.1.2 Transmission Electron Microscope

An electron microscope is a microscope that uses a beam of electrons to illuminate a specimen and create a highly magnified image [2]. Electron microscopes have much greater resolving power than light microscopes and can obtain much higher magnifications of up to 2 million times, while the best light microscopes are limited to magnifications of 2000 times. Both electron and light microscopes have resolution limitations, imposed by the wavelength of the radiation they use. If group of electrons, initially of zero energy, pass through a potential difference V then wavelength of electron will be

$$\lambda = \sqrt{\frac{150}{V}}$$

where, λ is in Å and the applied voltage is in volts [3]. The greater resolution and magnification of the electron microscope is because the de Broglie wavelength of an electron is much smaller than that of a photon of visible light. The strength of electron techniques lies in the fact that the electrons can be focused using electromagnetic lenses (unlike X-rays). Because of this reason high resolution images as well as diffraction pattern can be obtained from specific regions.

Transmission Electron Microscopy (TEM) is an electron microscopy technique in which the beam of electrons is transmitted through a thin specimen. TEM gives high resolution inner view of the materials. The variation in electron intensity across the specimen can also be used to image strain fields, defects (e.g. dislocations and second-phase particles) and atomic columns.

Different imaging modes in TEM are:

Bright Field Imaging

This imaging mode in TEM uses intensity of the unscattered electrons to form the image. Contrast in such an image is entirely due to thickness and density variations in the sample.

Convergent Beam Electron Diffraction

An electron probe is tightly focused on a TEM specimen and the resulting pattern of diffracted electrons is observed. The patterns contains information on the crystal symmetry and atomic and electronic structure of the sample. Regions as small as 0.2 nm may be examined.

Dark Field Imaging

In this mode a single diffracted beam is used to form the image. This causes all regions of the specimen not of the same crystal structure and orientation as the region which produced the chosen diffracted beam to be represented as very dark in the final image; allowing phase differentiation visually in the TEM.

Hi-Resolution Imaging

In this mode direct imaging of the specimen lattice is done. This is accomplished by allowing some of the diffraction image to overlay the bright field image. This enhances the contrast along the lattice lines and allows direct measurement of lattice parameters, inspection of individual defects and grain orientations.

Selected Area Electron Diffraction

In this mode an aperture is used to define the area from which a diffraction pattern is formed in a TEM specimen. The resulting patterns contain information about phases present (lattice spacing measurement) and crystal orientation.

2.1.3 Electron Diffraction Pattern

Transmission electron diffraction is a powerful method for characterizing the structure of materials [2, 3]. Fig. 2.2 shows a schematic sketch for transmission electron diffraction of an electron beam from a thin specimen. In this an electron beam incident on the specimen undergoes Bragg's diffraction similar to an X-ray beam. A screen is placed at a distance *L* from specimen perpendicular to the incident beam. An arrangement of spots due to different diffracted electron beams is observed.

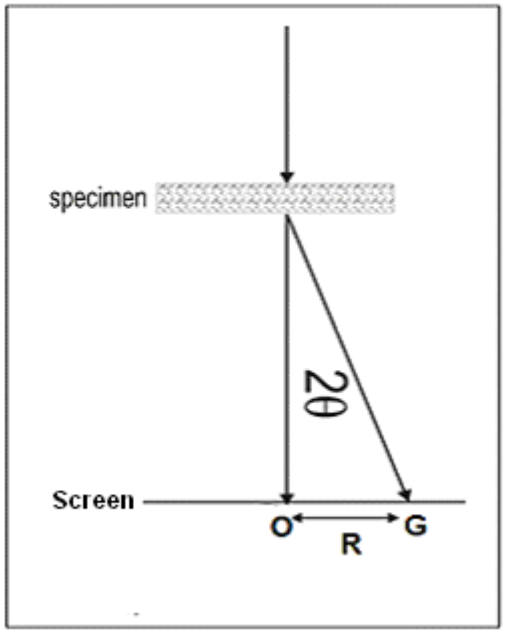

Fig. 2.2: Schematic sketch for electron diffraction from a crystalline material.

According to Bragg's law

$$2d \sin\theta = n\lambda \tag{2}$$

If *R* is distance of a spot from the centre then

$$\tan 2\theta = \frac{R}{L} \tag{3}$$

In such arrangements, usually the angle *θ* is very small. Using equations (2) and (3)

$$d = \frac{nL\lambda}{R} \tag{4}$$

Thus by measuring the distance of a spot form the centre in the electron diffraction pattern the corresponding *d* values can be calculated.

The Electron diffraction pattern is obtained in the same setup as used for the TEM imaging.

2.2 Thermal Characterization Techniques

Thermal analysis comprises a group of techniques in which a physical property of a substance is measured as a function of temperature, while the substance is subjected to a controlled temperature program [4]. Thermo gravimetric analysis and differential thermal analysis have been used for thermal characterization of the sample.

2.2.1 Thermo Gravimetric Analysis

Thermo gravimetric analysis (TGA) is an analytical technique used to determine thermal stability and fraction of volatile components by monitoring the weight change that occurs as a specimen is heated [5]. The measurement is normally carried out in air or in an inert atmosphere, such as Helium or Argon, and the weight is recorded as a function of increasing temperature. A maximum temperature is selected such that the specimen weight becomes stable at the end of the experiment, implying that all chemical reactions are completed. This provides information regarding the residual mass and the oxidation temperature, if any, for the sample.

2.2.2 Differential Thermal Analysis

Differential thermal analysis (DTA) involves heating a sample and an inert reference under identical conditions, and recording any temperature difference between the sample and the reference. This differential temperature is then plotted against time, or against temperature [6]. The absorption or evolution of heat in the specimen can then be detected relative to the inert reference. DTA can therefore

be used to study thermal properties and phase changes which occur due to change in temperature of the sample. The main components of a differential thermal analyzer are

(i) Thermocouples, sample containers (Crucibles).
(ii) Furnace or Heating Coil
(iii) Temperature programmer
(iv) Recording system

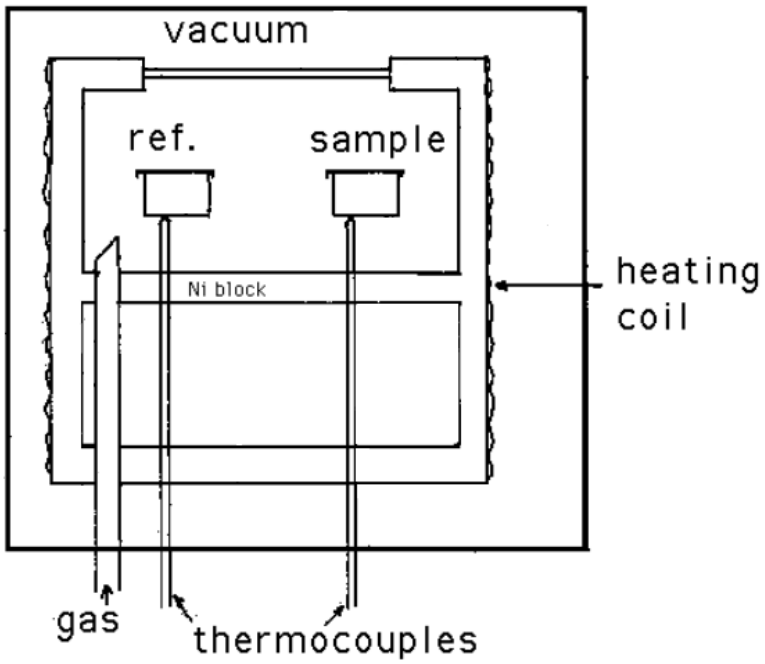

Fig. 2.3: Schematic illustration of a DTA set up. [7]

A schematic diagram for DTA is shown in Fig. 2.3. The DTA setup consists of a thermocouple each for the sample and reference, surrounded by a block to ensure an even heat distribution. The sample is contained in a small crucible. The material

of the crucible depends on the temperature and nature of the materials involved. In DTA, the thermocouples should not be placed in direct contact with the sample to avoid contamination and degradation. The apparatus is calibrated with materials of known melting points.

The essential requirements for the heating coil are that it should be able to provide a stable and sufficiently large temperature and must be able to respond rapidly to the temperature programmer. A temperature programmer is essential in order to obtain constant heating rates. Slower heating rates will give better resolution.

2.3 Vibrating Sample Magnetometer

Vibrating sample magnetometer (VSM) is an instrument that is used to study the magnetic properties of a given sample [8]. This instrument operates on Faraday's Law of Induction, which tells us that a changing magnetic field will produce an electric field. This electric field can be measured and can tell us information about the changing magnetic field. In vibrating sample magnetometer a sample is placed inside a uniform magnetic field to magnetize it. The magnetized sample is allowed to vibrate inside a pick up coil vertically. There is an induced voltage in the pickup coil because of Faraday's Law of Induction. This voltage is proportional to the magnetic moment of the sample, but does not depend on the strength of the applied magnetic field. Thus by measuring the induced voltage across the pickup coil it is possible to measure the magnetic moment of the sample.

Usually an electromagnet, which produces a maximum magnetic field of about 2 T, is used to produce magnetic field in vibrating sample magnetometer. For getting magnetic fields more than this superconducting magnet is used. Vibrating

sample magnetometers normally operate over a temperature range of 2.0 to 1050 K. Magnetization of materials in form of powders, solid and thin films can be measured.

Fig. 2.4: VSM setup used for magnetization measurements. [9]

2.4 Sample Details

Ferritin used in this work is the Horse spleen Ferritin purchased from Sigma, (product number 96701). As purchased sample consists of Ferritin molecules having concentration of 50-150 mg/ml in 150 mM saline solution.

2.5 Sample Preparation and Experimental Details

Preparation of powder sample: Ferritin solution is dried under vacuum.

XRD: Ferritin is characterized by X-ray diffraction using Seifert diffractometer and Cu K_α radiation (wavelength=1.542 Å). The diffractometer has a step size of 0.05^o, and the scan rate for the experiment was 3^o per min. Powder sample is used for this purpose.

TEM: Ferritin is characterized by TEM at operating voltage of 120 keV. For this a diluted drop of the as purchased Ferritin solution is placed on the copper grid and allowed to dry. The imaging is done in the Bright Field mode.

VSM: Magnetic characterization of Ferritin is done by VSM using applied field up to 17500 G at a room-temperature. The sample used is in powdered form.

TGA: Ferritin is characterized with TGA by heating about 18 mg of powdered sample from room temperature to 1200 K and recording the residual mass.

DTA: Ferritin is characterized with DTA by heating the powder sample from room temperature to 1200 K at a rate of 10 K per minute.

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CHAPTER 3
STRUCTURAL ANALYSIS

3.1 X-ray Diffraction

Room temperature x-ray diffraction pattern of Ferritin is obtained using a Seifert diffractometer and Cu K_α (wavelength λ=1.542 Å) radiation. This pattern is shown in Fig. 3.1. Such pattern shows sharp peaks if the sample is crystalline in nature. There is no sharp peak in this figure. Thus the Ferritin is amorphous in nature.

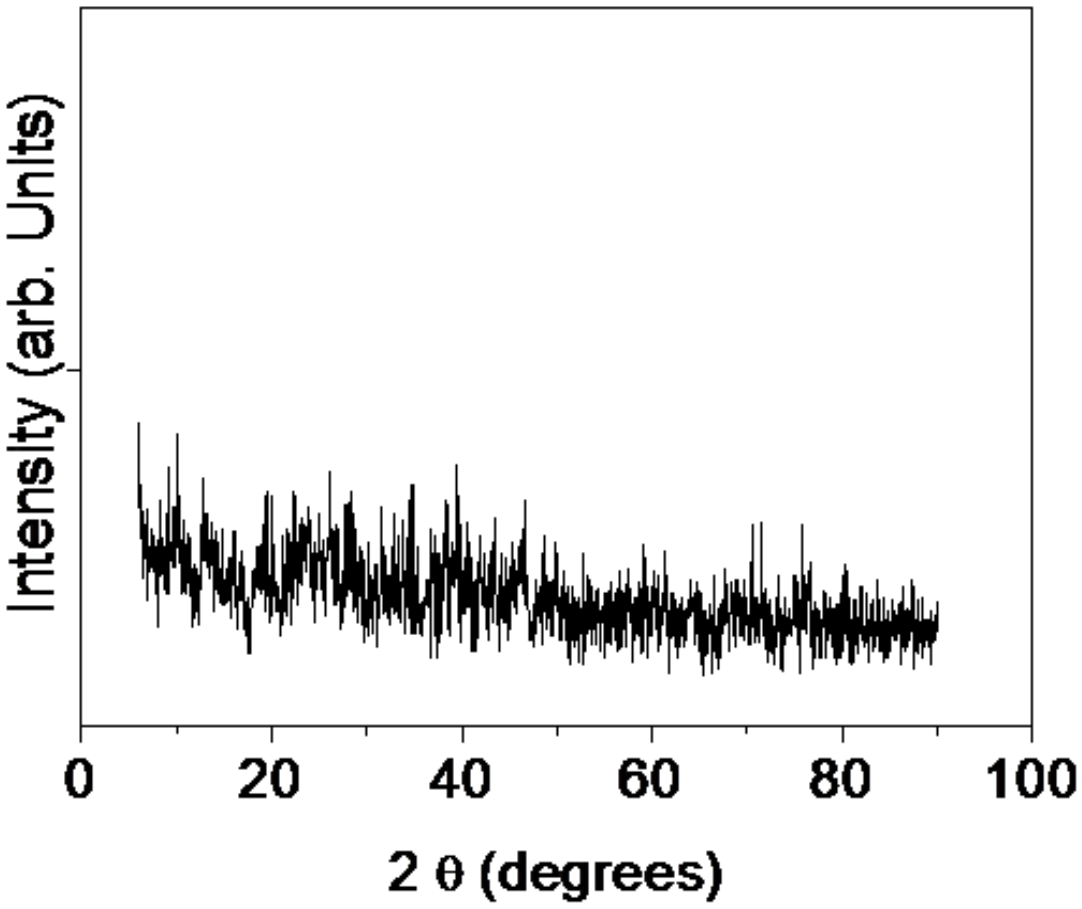

Fig. 3.1: Room temperature X-ray diffraction pattern of Ferritin.

3.2 Particle Size Analysis

Particle size analysis involves a size detection method coupled with a weighing method. In this particular case the size analysis has been done by analysis of Bright Field TEM images of Ferritin molecules.

The transmission electron micrographs obtained from different positions on the grid are shown in Fig. 3.2.

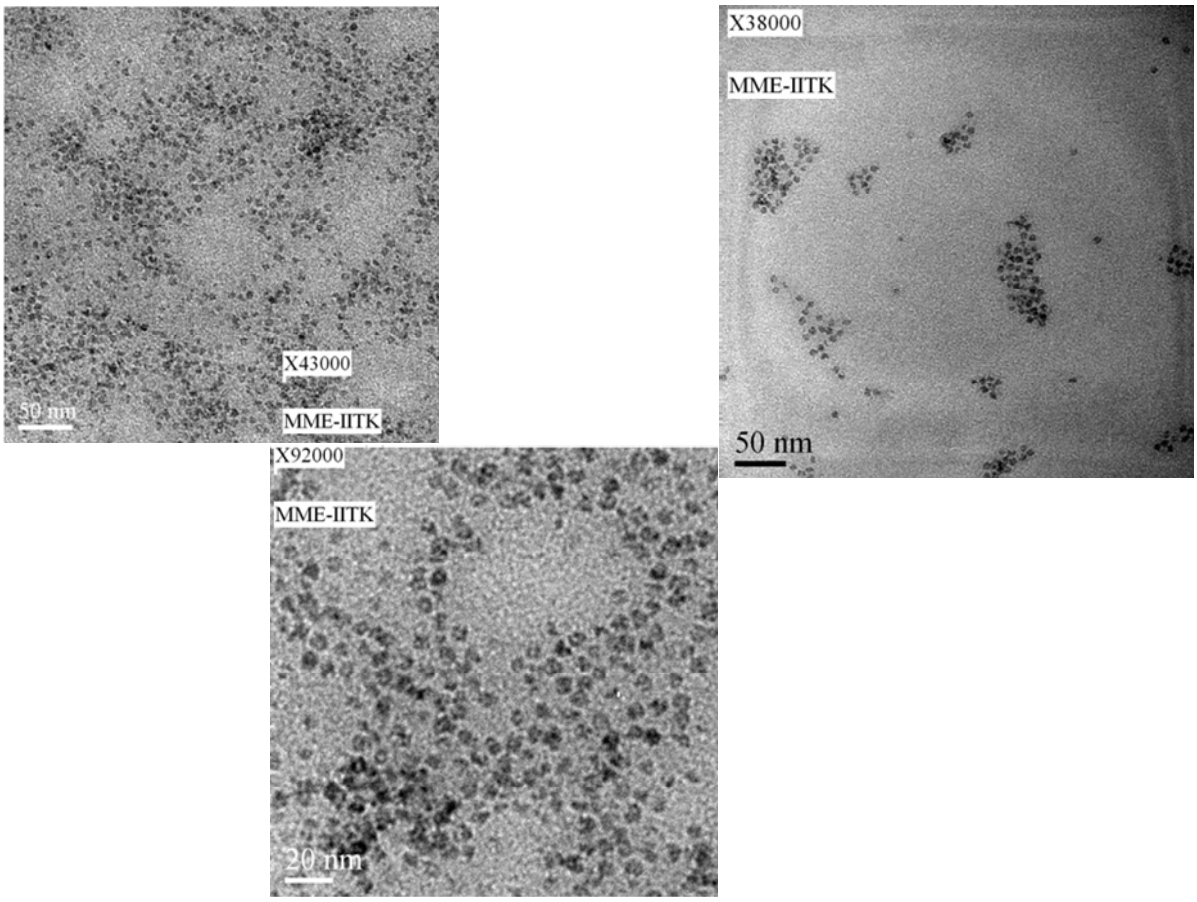

Fig. 3.2: TEM micrographs of Ferritin.

The steps involved in particle size analysis from TEM micrograph are:

1. Divide each TEM micrograph into areas of interest in Fig. 3.3.
2. Export these areas of interest to SPIP (commercial image analysis software).
3. In a Bright field TEM micrograph, the molecules come out as dark entities. For ease of analysis the image is inversed. And also do smoothening to reduce the noise in the image in Fig. 3.3.
4. Only those particles which are completely inside the area of interest and non-overlapping are analyzed.

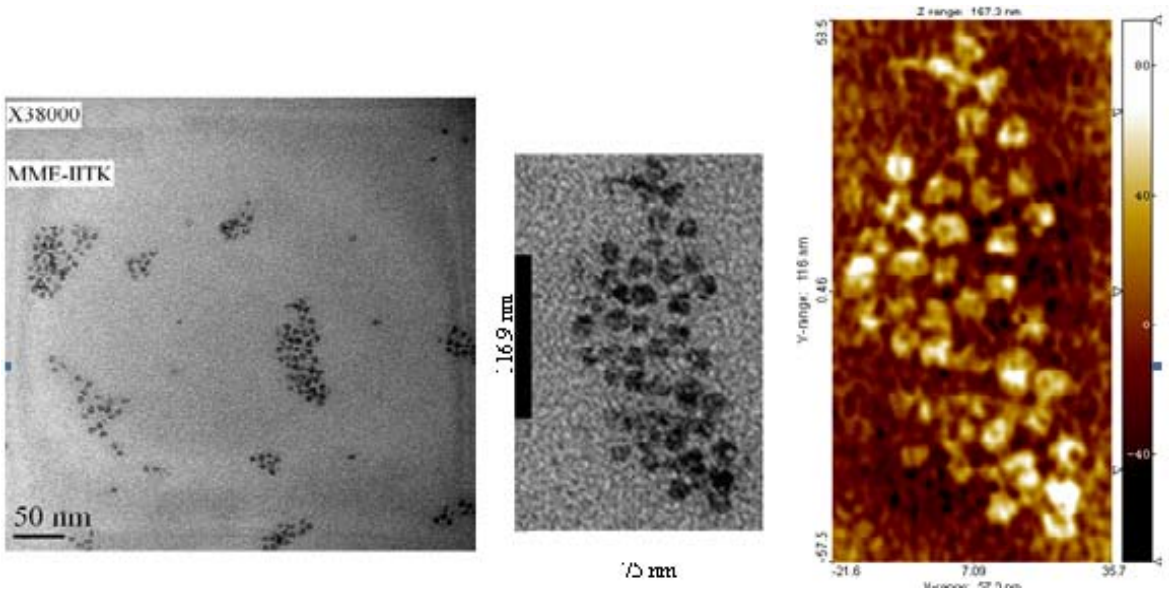

Fig. 3.3: (L-to-R) First image shows full TEM image of Ferritin particles. Second image is the area of interest. Third image is inverted and smoothened.

Using the above method total 410 particles were analyzed from the TEM micrographs. To determining the average size of the particle the probability distribution vs. particle size is plotted as shown in Fig. 3.5. The distribution is Gaussian in this figure. Average particles size from particle distribution comes out to be about 8 nm.

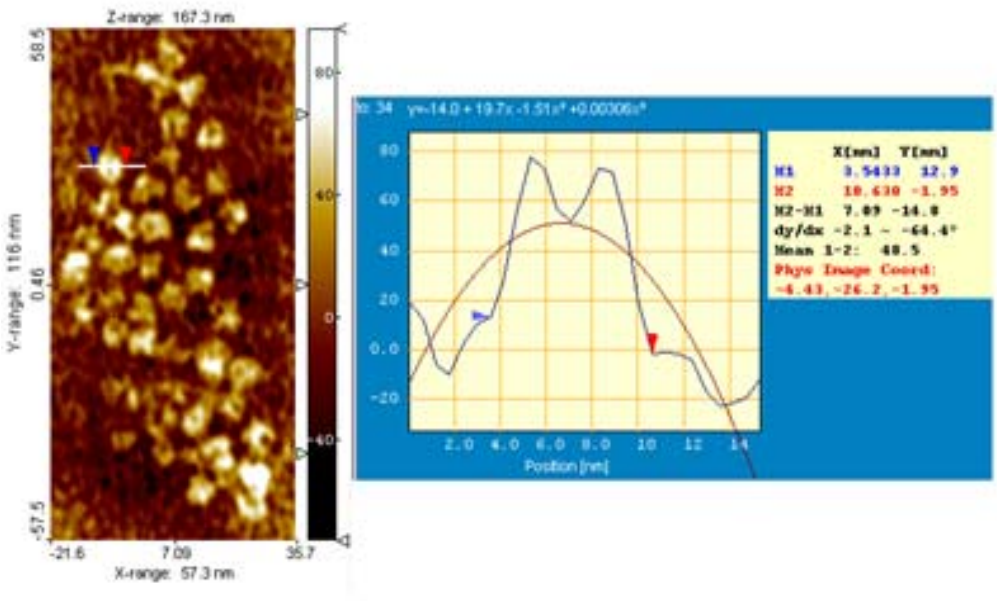

Fig. 3.4: Particle size determination.

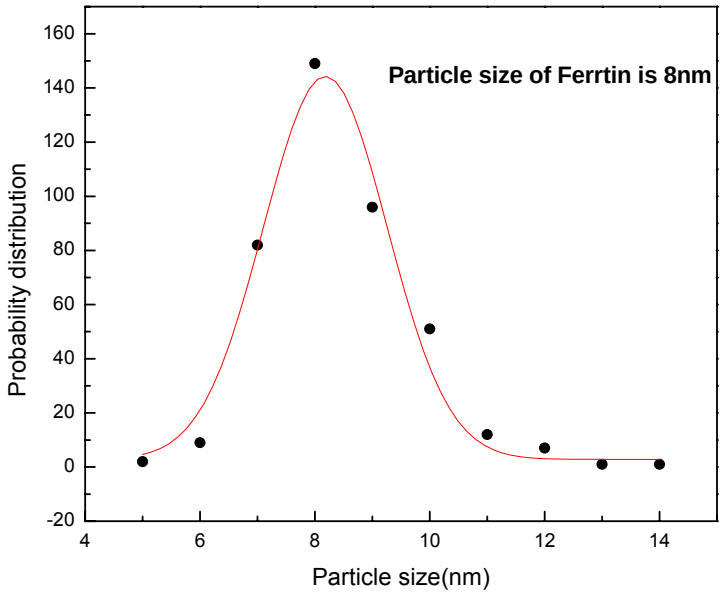

Fig 3.5: Probability vs. particle size distribution curve.

3.3 Electron Diffraction

The electron diffraction pattern from Ferritin is shown in Fig. 3.8. Electron diffraction pattern from a single crystal consists of a number of spots. Whereas the same consists of bight rings in the case of randomly oriented small particles.

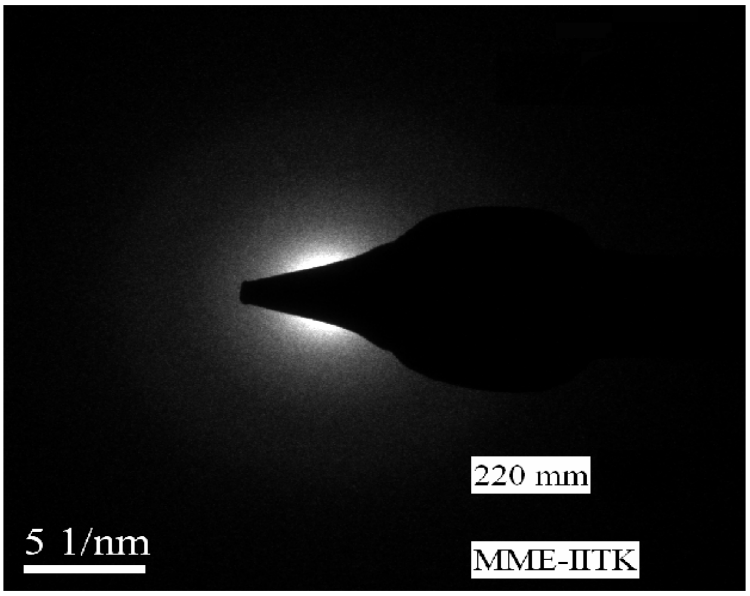

Fig. 3.6: Selected area electron diffraction pattern from Ferritin particles.

The selected area electron diffraction pattern from particles, shown in Fig. 3.6 There is no ring in this image. This again confirms that the Ferritin sample is amorphous in nature.

CHAPTER 4
THERMAL ANALYSIS

There are many materials in nature which are not stable at higher temperatures and decompose on heating. To check the stability of Ferritin at higher temperatures it is characterized using thermo gravimetric analysis and differential thermal analysis.

4.1 Thermo Gravimetric Analysis

Thermo gravimetric (TG) analysis is a technique in which the mass of a substance is measured as a function of temperature while the substance is subjected to a controlled temperature program. The variation of mass of Ferritin as a function of temperature is shown in Fig. 4.1. This figure shows that the mass of Ferritin decreases with increasing temperature continuously with a sudden change in its mass at about 800 K. Above to this temperature the mass of the material becomes almost constant over a range of temperature. This analysis indicates that there may be a change in phase of the sample at about 800 K.

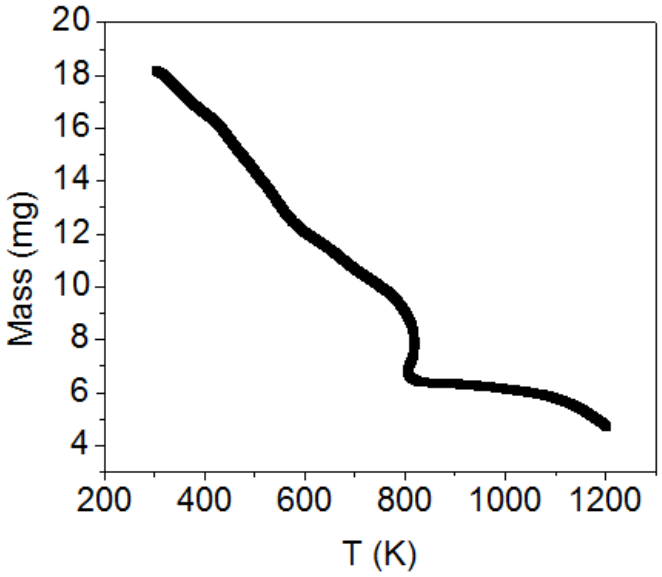

Fig. 4.1: Variation of mass of Ferritin as a function of temperature.

4.2 Differential Thermal Analysis

Differential thermal analysis is a technique in which the temperature difference between a substance and a reference material is measured as a function of temperature while the substance and reference material are subjected to a controlled temperature program. This variation, recorded at a heating rate of 10 K per minute, is shown in Fig. 4.2. This figure shows that there is very intense exothermic peak at about 800 K. Above this temperature the variation in DTA curve become almost independent of temperature.

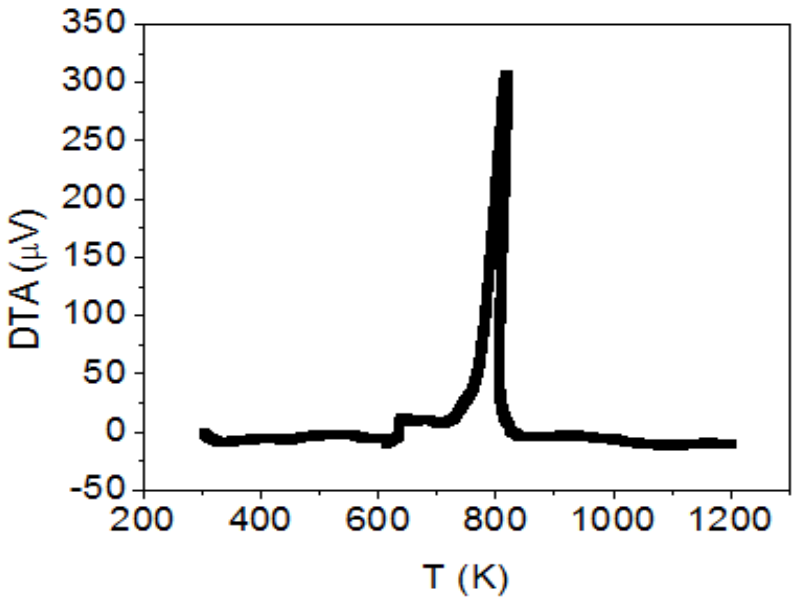

Fig. 4.2: DTA curve for Ferritin.

The intense exothermic peak in this analysis again indicates that there may be a change in the phase of the material at about 800 K.

Thus both thermo gravimetric and differential thermal analysis indicate a change in the phase of core of Ferritin at about 800 K.

CHAPTER 5

MAGNETIZATION MEASUREMENTS

Magnetization of Ferritin as a function of magnetic field at room temperature is measured using a vibrating sample magnetometer. This measurement is shown in Fig. 5.1. From this figure it is seen that there is no hysteresis in the M vs. H curve and the magnetization increases with increasing magnetic field strength. At lower magnetic fields the magnetization increases with magnetic field nonlinearly whereas at relatively higher magnetic fields the magnetization increases with magnetic field almost linearly. These are characteristics of antiferromagnetic materials. Saturation of magnetization is not observed in this measurement because antiferromagnetic materials usually require very high magnetic field to saturate.

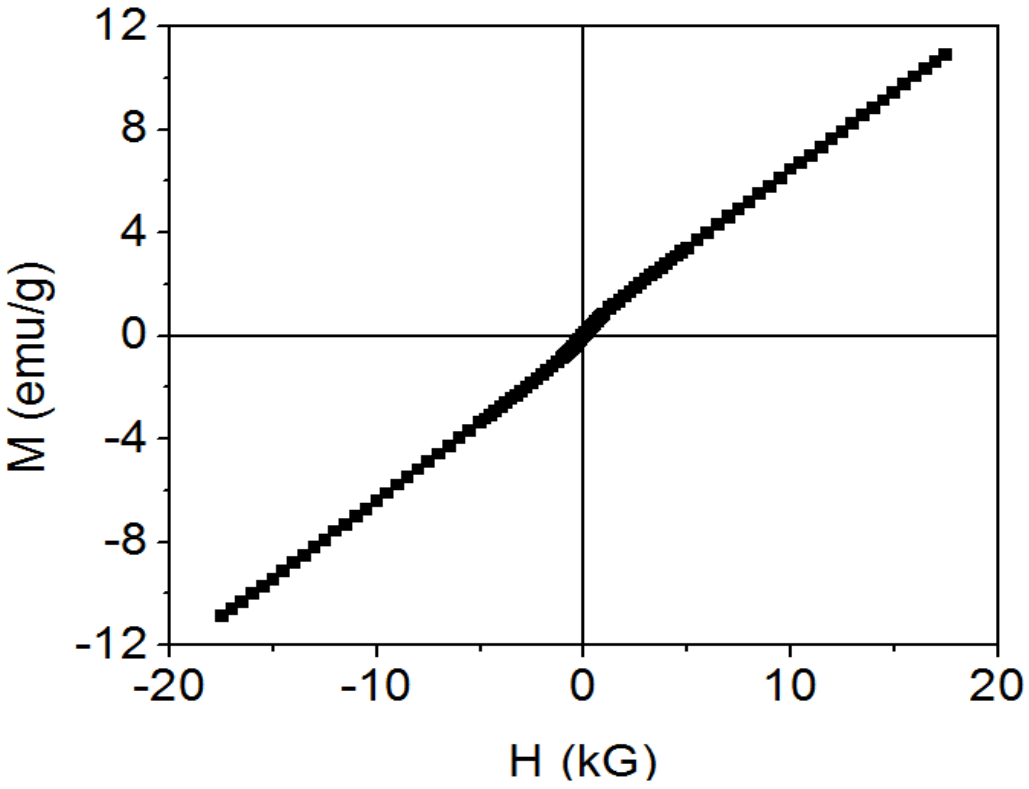

Fig. 5.1: Magnetization vs. magnetic field curve for Ferritin at room temperature.

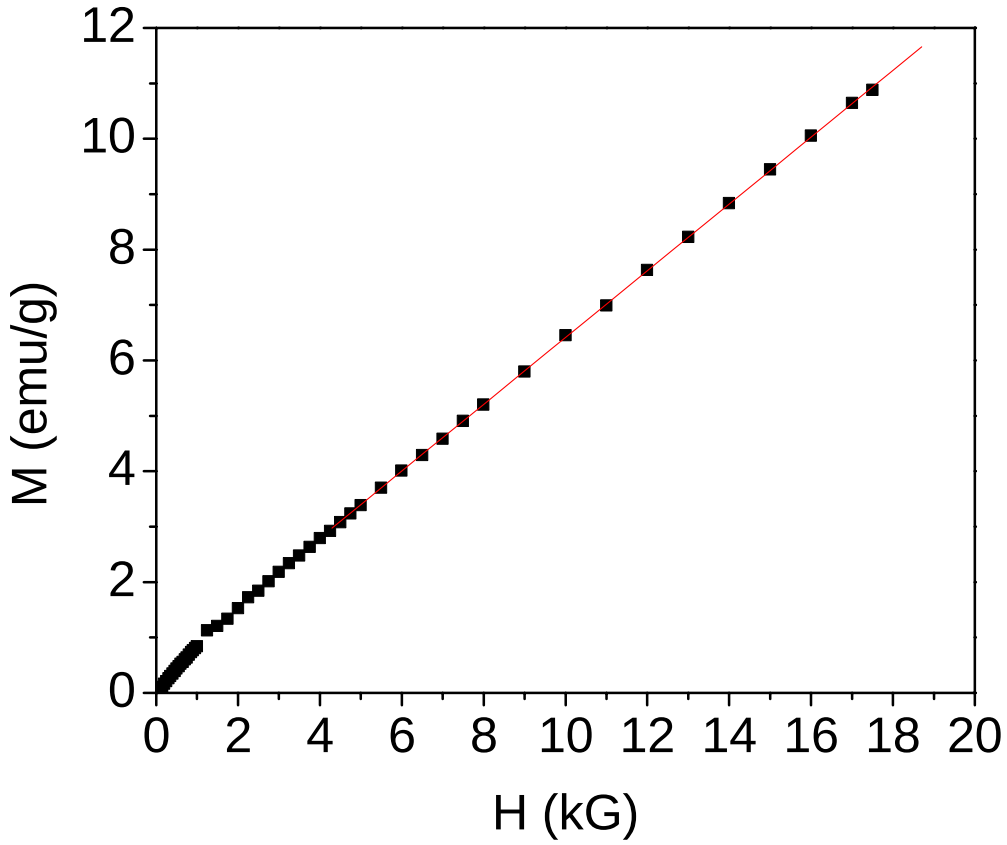

Fig. 5.2: Magnetization vs. magnetic field curve for Ferritin at room temperature. Solid line is the linear fit.

Magnetic susceptibility of any material is the ratio of the magnetization to the applied magnetic field in a region where the magnetization varies linearly with applied magnetic field. The magnetic susceptibility of Ferritin can be calculated using the linear portion of the magnetization versus magnetic field data shown in Fig. 5.1. A portion of magnetization versus magnetic field curve shown in Fig. 5.1 is again shown in Figure 5.2. The solid line in this figure is linear fit to the data. The fit is good with coefficient of determination R^2 equal to 0.99992. The slope of this

linear fit gives the magnetic susceptibility of Ferritin. It comes out to be about 6.0 × 10^{-4} emu / g Oe. Nickel oxide, an antiferromagnetic material, has magnetic susceptibility of 8.0 × 10^{-6} emu / g Oe at room temperature [1]. If magnetic susceptibilities of Ferritin and nickel oxide at room temperature are compared then the susceptibility of Ferritin is found to be much larger than that of bulk nickel oxide.

A bulk antiferromagnet has zero net magnetic moment in zero applied magnetic field. If the surface to volume ratio, which varies as the reciprocal of the particle size, for an antiferromagnetic particle becomes sufficiently large then the particle can have a detectable magnetic moment because of uncompensated spins at the surface. The large value of magnetic susceptibility of Ferritin compared to other bulk antiferromagnetic materials may be because of uncompensated spins at the surface of Ferritin [2].

References

[1] J. R. Singer, Phys. Rev. **104**, 929, 1956.

[2] S. A. Makhlouf, F. T. Parker, F. E. Spada and A. E. Berkowitz, J. Appl. Phys. **81**, 5561, 1997.

CHAPTER 6

CONCLUSIONS

Conclusions

The horse spleen Ferritin is characterized by x-ray diffraction, transmission electron microscope, thermal analysis and vibrating sample magnetometer. After this study following information about Ferritin is concluded.

(a) It is amorphous.

(b) It is almost spherical in shape with an average particle size of about 8 nm.

(c) The core of ferritin undergoes a phase change at about 800 K.

(d) It is antiferromagnetic at room temperature.

(e) Its magnetic susceptibility at room temperature is about 6.0×10^{-4} emu / g Oe.

Scope for Future Work

The Néel temperature is a characteristic parameter for any antiferromagnetic material. The Ferritin is an antiferromagnetic nanoparticle but its Néel temperature is not correctly known. Thus there is still scope for good work on Ferritin. Since Ferritin is antiferromagnetic at room temperature, so its Néel temperature must be above the room temperature. Determination of Néel temperature of Ferritin may be done by someone in future. However thermal decomposition of Ferritin will be a great barrier in determination of its Néel temperature.