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A Study of Magnetization in Antiferromagnetic Nanoparticle Systems

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Abstract - The purpose of the study is to Magnetization of superparamagnetic system depends on temperature, external magnetic field and time. It also depends on any history. The study shows zero field cooled (ZFC) and field cooled (FC) susceptibilities are plotted as a function of temperature T in the study. First, the system is cooled from room temperature to low temperature without the application of a magnetic field in order to assess ZFC susceptibility. Consequently, magnetic moments of particles are blocked in random directions. The next step is to apply a weak magnetic field and then collect data. This measurement relies heavily on the length of time it takes to collect data. By changing the frequency of the applied ac magnetic field, this observation time can be adjusted in ac magnetization measurements. Dc magnetization measurements use a time scale of about 100 milliseconds. We obtain a modest magnetization when the particle's magnetic moments slowly relax in the direction of the applied field. A particle's relaxation time depends on its temperature and size. As the temperature rises, the relaxation time reduces for a particular magnetic nanoparticle system. It is because of this that the magnetization increases as the temperature rises. When relaxation time equals observation time, the ZFC magnetization reaches its peak. For every degree increase in temperature above this limit, a drop in ZFC magnetization can be observed. FC magnetization is measured by cooling the system from room temperature to low temperature in the presence of an external weak magnetic field. Most of the magnetic moments of the particles are aligned with the field direction throughout this procedure. As a result, a substantial magnetization can be achieved at low temperatures. Increasing the temperature causes this magnetism to diminish at an almost constant rate. Blocking temperature TB is the temperature where the ZFC and FC curves meet, and bifurcation temperature Tbf is where the ZFC and FC curves meet. The system is in a blocked condition below the bifurcation temperature, whereas it stays in a superparamagnetic state above it.

Keywords - Magnetization, Antiferromagnetic, Nanoparticle Systems, zero field cooled (ZFC), field cooled (FC)

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INTRODUCTION

The development of materials science has been used as an indicator of human civilization's progress. The study of materials is a highly interdisciplinary endeavor that draws on a wide range of disciplines, including physics, chemistry, engineering, and biology. Materials science encompasses a wide range of fields, including thermodynamics, crystallography, solid state physics, polymer science, biology, and so on. As new information about materials science becomes available, new subfields continue to emerge. One example is nanotechnology. One of the oldest engineering and applied sciences is materials science. The primary concerns of materials science are the structural and physical properties of various materials. New materials with improved performance are now being created based on the fundamental understanding of the structure-property relationship. Depending on how they interact with the environment, materials can be classed. For example, semiconductors, magnetic materials, etc., are all examples of functional materials that perform a specific function for a given application. For structural materials, the mechanical qualities of these materials are the most significant consideration. Other features are less important. Steel, plastic, rubber, and so on. Two-way communication: This type of substance reacts to its environment in a reciprocal manner. They are able to detect changes in their environment and send a signal to their handlers that tells them what to do next. Piezoelectric materials, shape memory alloys, magnetostrictive materials, magneto-rheological fluids, and others are referred to as "intelligent materials."

All matter, according to Dalton, consists of a single unit known as an atom. For a solid to develop, many atoms must get close together. In three dimensions, atoms can arrange themselves in a regular and periodic pattern. Crystals are the name given to such solids. Crystal structures have the lowest configuration energy, hence they make up the majority of all natural solids. Crystalline substances respond differently to electric, magnetic, and optical fields applied externally. Materials can be categorized based on how they respond. It's common for electrons in the outermost orbit to play a significant role in determining the overall atomic structure and conductivity. By using an external electric field, it is possible to remove electrons from their parent atoms that are weakly bonded. They're called conduction electrons, and they're capable of transferring electricity. To classify materials according to their electrical conductivity, we can divide them into conductors, semiconducting and non-conducting. Thermal energy can likewise be transported via these electrons. Electrons in materials can be easily changed by applying electromagnetic waves of an appropriate frequency to their quantum states. This results in a variety of optical effects. The orbital motion around the nucleus plus the spin about its own axis give electrons in atoms a net magnetic moment. In most cases, the orbital contribution is reduced to a negligible amount, leaving electronic spin as the primary source of atomic magnetic moment. The nucleus is sometimes overlooked, despite making a considerably smaller contribution. All known crystalline solids can be divided into diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic, and ferrimagnetic categories based on their magnetic properties [1–3].

NANOMATERIALS

Nanomaterials can be found and used in a variety of ways in various locations. This is also true in nature. Natural nanomaterials such as ferrihydrite and ferritin are the greatest examples. In contrast, the first one may be found in dirt, whereas the second one can be found in the blood of mammals. Most nanomaterials, on the other hand, are manufactured in the laboratory using appropriate chemical and physical processes [7–8]. Nanomaterials have piqued the interest of scientists and engineers from a wide range of fields in recent decades due to their unusual properties and potential usage in a variety of technological applications. The size and surface effects of certain materials cause them to behave differently than they do in bulk. Energy bands are seen in bulk materials. In these materials, the number of atoms exceeds Avogadro's number. Because the spacing between the electronic energy levels in energy bands is so small, these levels are treated as continuous for all intents and purposes. Use this theory to comprehend bulk solids in terms of their electrical, optical, and magnetic properties. As any or all bulk material dimensions shrink to the nanoscale scale, conduction electrons' movement is restricted. As a result, the de Broglie wavelength is larger than the nanomaterials' size in such a circumstance. Distinct electronic energy levels are no longer applicable to the band theory. For the quantum size effect to be realized, the average distance between energy levels must be greater than the thermal energy [8]. Surface atoms in any crystal are subject to a variety of abnormalities. Nevertheless, the total number of atoms in a bulk crystal is so small that the number of atoms resting on the surface is practically nonexistent. As a result, bulk crystals do not suffer from the same effects as their surfaces. However, when a crystal's dimension is shrunk down to the nanometer range, a considerable portion of the total atoms are visible on top. When defining the overall behavior of the material, these surface atoms cannot be neglected [8].

PROPERTIES OF NANOMATERIALS

Reduction in size of crystalline solids alters its overall behavior. The variation in important features of solids due to reduction in size is summarized as follows.

1. Physical properties

Interatomic forces hold atoms together in solids. These atoms are able to overcome interatomic forces when they reach the melting point. As a result of surface irregularities, the average strength of these internal forces is reduced. Consequently, the melting points of nanomaterials are lower than the melting points of their larger counterparts. The melting point of bulk germanium is 930^0C, but the melting point of germanium nanowire is 650^0C [8, 13]. Dislocations and other lattice flaws can also be found in bulk materials. By lowering the material's dimensions, this fault can be eliminated. Nanomaterials are tougher than their bulk counterparts because of this. It is five times harder to work with 6 nanometer copper particles than it is with 50 micrometer copper grains, for example [8].

2. Chemical properties

Chemical reactions are aided by atoms' valance electrons. Reducing the size of a substance increases its surface atom count. Because of this, the chemical reacts more readily. The catalytic activity of other catalysts is likewise increased for the same reason [14].

3. Electrical properties

The quantum size effect governs electron conduction in nanomaterials. Thermal energy must be smaller than the typical distance between electronic energy levels in order to see this impact. A nonlinear relationship exists between metal current and applied voltage in this scenario. It is, in reality, a staircase-like structure. Research on quantum dot I-V characteristics [15] has been done. When the applied voltage surpasses e 2C, the particle's capacitance, no current flows. Steps in current flow through the system occur when the applied voltage is 2e 2C, 3e 2C and so on. Coulomb blockade is the name given to this phenomenon.

4. Optical properties

The band gap of optically active materials decreases as a result of the quantum size effect. The absorption peak changes to lower wavelengths as a result of this. As the crystal size increases, the material's color appears to alter as well. Because of surface plasmon resonance, metallic nanoparticles can change color. When the incident radiation's wavelength grows larger than the nanocrystals', a resonance arises. In nanowires, the same phenomenon is found. However, two surface plasmon resonance modes can be found here. This one is longitudinal, whereas the other one is transverse. At the nanoscale, gold and silicon appear red, whereas their bulk counterparts are yellow and grey [8].

5. Mechanical properties

The existence of many crystal flaws reduces a material's mechanical strength. Nanomaterials, on the other hand, are virtually defect-free and as a result possess tremendous mechanical strengths. Steel, for example, is significantly more durable than carbon in mass. The steel is, nevertheless, found to be significantly weaker than carbon nanofibers [11].

6. Magnetic properties

Size and surface effects have a significant impact on the magnetic nanoparticles' behavior. It is commonly known that these systems exhibit unusual behavior. For example, a phenomena known as superparamagnetism can only be observed in extremely small magnetic particles. This displays Paramagnetism-like activity in a cluster of tiny magnetic material particles. Particles of ferro- and ferrimagnetic materials have been widely researched for their superparamagnetic properties. The surface effect has a significant impact on the magnetization of magnetic nanoparticles. The smallest details on the surface are in a state of disarray. Saturation magnetization diminishes with decreasing particle size as a result of this [12]. Nonetheless, antiferromagnetic particles behave differently in a same circumstance. The net magnetic moment of a bulk antiferromagnetic is zero. However, the disordered surface moments in antiferromagnetic nanoparticles provide a particle magnetic moment that can be detected, whereas the core does not. As a result, as particle size decreases, antiferromagnetic particles' magnetism increases. Small magnetic particles can also be used in a variety of technological fields. Magnetic recording material is the primary use for these devices. The magnetic moment of particles is aligned in a precise direction to record a specific digital signal. Magnetic moments in particles must have a fixed orientation. The stored data will be lost if the same occurs over time. In order to enhance store capacity, recording media employs smaller particles. However, particles must be big enough to prevent the system from entering a superparamagnetic state. In a second system, the non-magnetic fluid comprises a dispersion of ferro and ferrimagnetic nanoparticles. The dipolar contact between particles is substantially less when fluid is present. Additionally, magnetic nanoparticles are playing a significant role in the delivery of specific drugs. To do this, drug-loaded biocompatible magnetic nanoparticles are functionalized. An external magnetic field is employed to focus these particles on the damaged location inside the body. In the future, cancer and tumor cells may be treated with this technology. This strategy ensures that cytotoxic medications are distributed in a consistent manner, reducing the risk of adverse effects. Hyperthermia can also be utilized to kill cancerous or tumorous cells, and is referred to as such. When exposed to temperatures between 41 to 47^0C, tumor cells die more quickly than normal cells. Magnetic nanoparticles are delivered to the tumor, and an external alternating magnetic field is used to generate heat in order to obtain the appropriate temperature.

MAGNETIC MATERIALS

All around us, magnetic materials exist. The development of magnetism is largely due to the tireless work of numerous individuals who have made significant contributions to our current understanding of this fascinating phenomenon. Since our ancestors discovered lodestone thousands of years ago, magnetic materials research has advanced dramatically. Many modern technologies rely heavily on magnetic materials. Magnetization, coercivity and remanence determine whether or not a magnetic substance can be used in a specific context. A variety of magnetic materials, including oxides and alloys, can be employed. Almost every aspect of our daily lives can benefit from the use of magnetic materials. There are numerous industrial uses for permanent magnets such AlNiCo and hard ferrites, Sm-Co magnets, Nd-Fe-B magnets, etc. Electrical engineering and power electronics utilise soft magnetic materials with high saturation magnetization, high permeability, and very low energy dissipation in a wide variety of applications. Telecommunications and electronics both make use of soft magnetic materials [1]. As well as ferrite memory cores in drum hard disk drives and floppy disk drives as well as magnetic field screenings, magnetic materials have also been used to store analog and digital data on videotapes and audiotapes as well as in magnetic field screenings. There is a bright future for several materials as a result of recent breakthroughs in magnetism, such as giant magneto resistive materials for use in GMR read heads and MRAMS. In the field of spintronics and magneto electronics, diluted magnetic semiconductors (DMS) are an important class of materials where magnetic ions are introduced into a semiconductor host lattice [2-4]. As a result, magnetic materials have been and will continue to be an essential element of the technological revolution.

Magnetism in Materials

All materials have a magnetic property [7]. The electrons in the atom, which have a modest magnetic moment due to their mobility, are the primary source of the magnetic properties. A tiny magnetic moment exists in the nucleus as well, but it is dwarfed by that of the electrons, thus it has no effect on the overall magnetic properties.

1. Magnetic Moments of Electrons

The orbital and spin motions of electrons each have a magnetic moment associated with them. The electron's orbital motion is analogous to the current flowing through a loop of no-resistance wire, and both represent the flow of charge.Therefore, the magnetic moment of an electron due to its orbital motion is given by,

$$\mu = (\text{area of loop})/(\text{current in emu})$$

If e is the charge on the electron in esu and c is velocity of light, then e/c is the charge in emu. The current or charge passing through a given point per unit time is thus

$$((e/c)(v/2\pi r)) \quad (1.1)$$

Therefore,

$$\mu_{orbit} = \pi r^2 \left(\frac{ev}{2\pi rc}\right) = \frac{evr}{2c} \quad (1.2)$$

The angular momentum of an electron is given by,

$$mvr = nh/2\pi \quad (1.3)$$

Combining these equations, we have the orbital magnetic moment for an electron in the first Bohr orbit,

$$\mu_{orbit} = eh/4\pi mc \quad (1.4)$$

No matter what the condition of matter or temperature, electrons always have spin. While travelling in an orbit around the nucleus, electrons behave as if they were spinning around their own axis and possessing magnetic moments and angular momentum. The magnetic moment due to electron spin is equal to,

$$\mu_{spin} = \frac{eh}{4\pi mc} \quad (1.5)$$

In this equation, e stands for the electron's charge, h stands for Planck's constant, m stands for the electron's mass, and c stands for light's velocity. Electron spin and orbital motion produce a magnetic moment of 0.927x 1020 erg/Oe when all the values in the equation are replaced. Bohr magnetons have been assigned a distinctive symbol, JJLB, because they are so fundamentally important. The field of magnetism has a number of fundamental notions. One such phrase is the magnetic moment. For example, if a magnetic pole is situated at an angle 9 to another magnetic pole and separated by the distance /, then a couple acts on the magnetic moment in the uniform magnetic field H. m and is given by,

$$m = pH\sin\theta(l/2) + pH\sin\theta(l/2) = (pH\sin\theta) \quad (1.6)$$

If $H = 1$ Oe and $\theta = 90°$,

$$m = pl \quad (1.7)$$

The magnetic moment per unit volume is called intensity of magnetization or simply magnetization and is given by,

$$M = \frac{m}{V} \quad (1.8)$$

where V is the volume of the material. The specific magnetization is defined as,

$$\sigma = \frac{m}{W} = \frac{m}{v\rho} = \frac{M}{\rho} emu/g \quad (1.9)$$

where W is the mass and p is the density of the material. The magnetic properties of a material are characterized not only by the magnitude and sign of M, but also by the way in which M varies with H.

The magnetization per unit magnetic field is called the magnetic susceptibility(x)-

$$\chi = \frac{M}{H} = emu/cm^3\,Oe \quad (1.10)$$

X is also called the volume susceptibility. Depending on the values and order of susceptibility, substances have been classified into different categories. The most important ones are Paramagnetism, ferromagnetism, ferrimagnetism, antiferromagnetism and superparamagnetism [7,8].

2. Diamagnetism

All materials have some degree of diamagnetism. Diamagnetism is the result of electrons in the inner shells of a substance interacting with each other. The field induces a very faint magnetization in them, and it points in the opposite direction of the applied field. Electronic orbital motion changes under the influence of a magnetic field, and this type of magnetism results. As stated in Lenz's law, the induced currents produce an induced magnetic flux that is in the opposite direction of the applied magnetic field. In all magnetic materials, dimagnetism is present, but it is obscured by the magnetic atoms. The negative susceptibilities of diamagnetic materials, which are independent of temperature and are on the order of 10-6, are well-known.

3. Paramagnetism

The permanent magnetic moment associated with some or all of the constituent atoms is the source of the magnetism in paramagnetic substances. Since their interactions with one another are minimal, these moments are free to move in any way. This phenomenon is known as free atom paramagnetism.

A net magnetic moment is connected with the atoms that make up a paramagnetic material. It is possible to generate a magnetization perpendicular to the applied field by changing the average moment direction. The lower the magnetization is as the temperature rises. As the temperature rises, the relationship between magnetization and field becomes increasingly linear. Temperature-dependent paramagnetic susceptibilities were discovered by Pierre Curie in 1895.

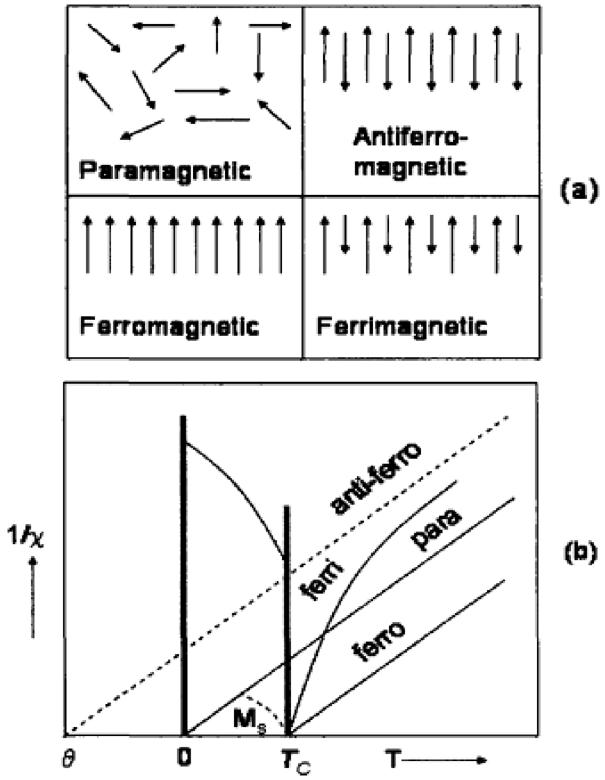

Figure 1: (a) Alignment of magnetic moments in different magnetic materials and (b) variation of the inverse susceptibility with temperature of para-, antiferro-,ferro- and ferrimagnetic materials

When it comes to paramagnetic substances' mass susceptibility, the absolute temperature has an inverse effect on it given by,

$$\chi = \frac{C}{T} \qquad (1.11)$$

This equation is known as Curie's law, where C is the Curie constant. The effective magnetic moment /ue// is directly related to the number of unpaired electrons present.

$$\mu_{eff} = g[J(J+1)]^{1/2}\mu_B \qquad (1.12)$$

The relationship between χ and effective magnetic moment μ_{eff} is given by,

$$\chi = \frac{N\beta^2\mu_{eff}^2}{3kT} \qquad (1.13)$$

where, N is Avogadro's number, β is the Bohr magneton and k is Boltzmann's constant. Substitution for N, β and K gives,

$$\mu_{eff} = \sqrt{8C} = 2.828\sqrt{C} \qquad (1.14)$$

When the orbital angular momentum is quenched L = 0 and therefore J = S, as in the case for most transition metal ions. The effective magnetic moment is contributed by the spin components only and is given by,

$$\mu_{eff} = 2\sqrt{S(S+1)} \qquad (1.15)$$

The alignment of magnetic moments and the variation of the paramagnetic susceptibility with temperature is shown in figure 1.

CONCLUSION

Two- and six-line ferrihydrites, as well as nickel oxide and two- and six-line ferrihydrite nanoparticle composites, were studied for structural, thermal, and magnetic properties in this dissertation. Transmission electron micrographs show that the average crystallite size measured by x-ray diffraction line broadening is very close to the average particle size. That each particle is a crystallite is clear from this finding. In addition, transmission electron micrographs indicate that particles can be of any shape or size. Upon heating in air, ferrihydrite nanoparticles of both types break down into hematite. Due to the finite size effect, all three studied systems are antiferromagnetic and display superparamagnetic behavior. Field cooled susceptibility is shown to peak at certain temperatures and decline monotonically with increasing temperature. 0 field cooled susceptibility at specific temperatures, both curves are shown to bifurcate. Magnetization relaxes slowly below this bifurcation temperature, resulting in hystereses in the M-B loops. However, because magnetization relaxes so rapidly above the bifurcation temperature, no hysteresis in the M-B loops can be observed. Systems are said to be in a superparamagnetic state when they are located in this region. System-specific magnetization data for each system has been analyzed thoroughly. The modified Langevin function is used to fit magnetization data on two and six lines of ferrihydrite nanoparticles. The applied magnetics field's range has an effect on the fit parameters' estimated values. That is, the data does not fit these parameters. Because particle size and shape are not considered in this analysis, there is no consideration given to the distribution of particle magnetic moments. A distribution of particle magnetic moment is taken into account while fitting the magnetization data to the modified Langevin function. It has been discovered that the predicted fit parameters are virtually independent of the applied magnetic field range, allowing them to accurately characterize the data this time. Both forms of ferrihydrite nanoparticles have their magnetization studied at various temperatures in the superparamagnetic zone as a function of the applied magnetic field. In this manner, the distribution of particle magnetic moments in each system can be approximated.

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