Physical Properties of Magnetic Materials of Cobalt Oxide, Iron Oxide and Manganese Oxide

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ABSTRACT

This review focuses on the physical properties of three magnetic materials: Cobalt oxide (Co_3O_4), Iron oxide (FeO), and Manganese oxide (MnO). These materials exhibit interesting magnetic behavior and have been extensively studied due to their potential applications in various fields, including spintronics, magnetic storage, and magnetic sensors. In this review, we provide a comprehensive overview of the physical properties of Co_3O_4, FeO, and MnO, including their crystal structures, magnetic properties, structural properties, electrical properties, and thermal Properties. We also discuss the factors influencing the magnetic properties of these materials, such as temperature, doping, and external magnetic fields. Additionally, we highlight the technological applications and challenges associated with these magnetic materials. This review serves as a valuable resource for researchers and scientists interested in understanding and utilizing the physical properties of Co_3O_4, FeO, and MnO.

Keywords:
Magnetic properties,
Co_3O_4,
FeO,
MnO,
Structural properties.

INTRODUCTION

Magnetic materials have attracted significant attention due to their fundamental properties and a wide range of technological applications (Kuppan *et al.,* 2017). Among them are Co_3O_4, FeO, and MnO. These three important magnetic materials exhibit distinct magnetic behavior. They are used to produce magnetic core, light and heat sensors, flexible electronic devices like artificial skin for robot etc (Ogale *et al*, 2000)

Magnetic materials play a crucial role in various technological applications, including data storage, sensing, and power generation. Among the numerous magnetic materials available, Co_3O_4, FeO, and MnO have garnered significant attention due to their intriguing physical properties (Santos *et al*, 2021). In this review, we will explore the physical characteristics, magnetic properties, and potential applications of these three materials.

Cobalt Oxide

Cobalt oxide (Co_3O_4) is a versatile magnetic material that has garnered significant attention in various scientific fields due to its unique physical properties (Liu *et al*, 2024). It's a black amorphous powder that forms cobalt (II, III) oxide when heated. Cobalt oxide is an unstable and unlikely free compound (Abdollah *et al.,* 2020). At room temperature and pressure, cobalt is a lustrous, hard, and brittle metal. It is one of three naturally occurring magnetic elements (the other two are iron and nickel).

This magnetic property stems from how the electrons are arranged within the cobalt atoms (Park *et al*, 2014). Electrons can have one of two configurations, either "spin up" or "spin down." When electrons are paired in an orbital, they are paired with one spin up electron and one spin down electron (following the Pauli Exclusion principal), canceling out any magnetic moment. However, in the case of cobalt, it has three unpaired electrons which all share the same configuration (following Hund's rule), so the magnetic fields of these unpaired electrons join together to give an overall magnetic atom. Additionally, cobalt retains its magnetic property to the highest temperature of all magnetic elements (1115 °C). The higher the temperature, the more likely materials are to lose their magnetic properties because the high temperature provides energy for the electrons to move around and change configurations, disrupting the magnetic field (Khan et al, 2024).Melting Point: 1495 °C = 2723 °F = 1768 K,Boiling Point: 2927 °C = 5301 °F = 3200 K, Density: 8.86 g cm^{-3}Phase at Room Temperature: Considering the physical properties of Cobalt oxide, and highlighting its magnetic behavior, crystal structure, electrical conductivity, and thermal properties and understanding these characteristics, one can harness the potential of cobalt oxide for diverse applications ranging from electronics to energy storage (Vennella *et al*, 2019).

Magnetic Properties
Cobalt oxide exhibits interesting magnetic behavior, making it a crucial material for magnetic studies (Liu *et al.,* 2024). It possesses antiferromagnetic properties, meaning that its magnetic moments align in an antiparallel configuration at low temperatures. The Néel temperature (T_N), which is approximately 291 K for cobalt oxide, signifies the transition temperature where the spins align and antiferromagnetic order sets in (Yang *et al.,* 2022). At room temperature, CoO is paramagnetic and, therefore, no dipole magnetic interactions are expected. Cobalt can be used to make both soft and hard magnets. Compared to other soft magnets, cobalt-based magnets have a number of advantages. In particular, their saturation point is high, with Curie temperatures within the range of 950...990° Celsius. Therefore, they can be used in high-temperature applications (up to under 500°C). Cobalt alloys are used in hard disks, wind turbines, MRI machines, motors, actuators, and sensors.

They are particularly suitable for spintronics and magnetic storage applications. (Vennela *et al*., 2019)

Crystal Structure
Cobalt oxide adopts a cubic crystal structure with a rock salt lattice. Each cobalt atom is coordinated by six oxygen atoms, forming an octahedral arrangement (Saha *et al.,* 2017). This structure provides insight into the magnetic and electronic properties of cobalt oxide, allowing researchers to manipulate its behavior through controlled doping and defect engineering. Co_3O_4 adopts the normal spinel structure, with Co^{2+} ions in tetrahedral interstices and Co^{3+} ions in the octahedral interstices of the cubicclose-packedlattice of oxide anions as shown in figure 1(a)(b) and (c) (Vennela et al, 2019). The spinel composites are considered potential candidates of catalytic material for use in energy fields due to their various advantages, like, low toxicity, high natural abundance, and versatility.
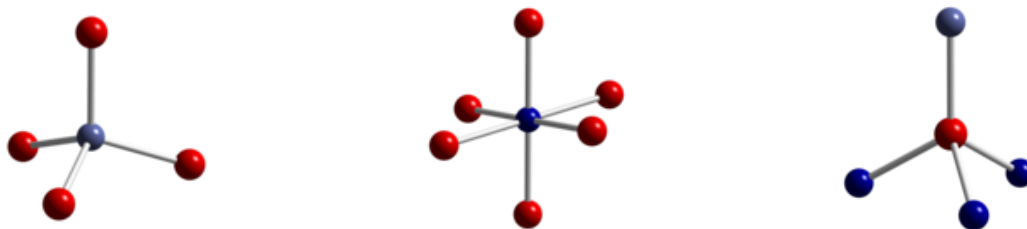

Figure 1: (a) tetrahedral coordination geometry of Co(II)

(b) distorted octahedral coordination geometry of Co(III)

(c) distorted tetrahedral coordination geometry of O

Electrical Conductivity
The electrical conductivity of cobalt oxide is influenced by its crystal structure and defect concentration (Baldini *et al*,2015). At room temperature, cobalt oxide exhibits semiconducting behavior, with a relatively low conductivity. However, by introducing oxygen vacancies or doping with other elements, its electrical conductivity can be enhanced, enabling applications in sensors, electrochemical devices, and catalysis. The conductivity of cobalt oxide based films exhibits ρ values between 10^{-3} Ωcm^{-1} , depending on the conditions of the annealing (Britannica encyclopedia, 2024)

Thermal Properties
Cobalt oxide possesses excellent thermal stability, making it suitable for high-temperature applications (Gawali, 2018). It has a relatively high melting point of around 1933°C and exhibits low thermal expansion coefficients. These characteristics, combined with its magnetic properties, render cobalt oxide an attractive material for magneto caloric refrigeration, where it can be used in heat pumps for efficient cooling.

Applications
The unique combination of physical properties makes cobalt oxide a promising material for various applications. In addition to its use in magnetic storage and spintronics, cobalt oxide finds applications in gas sensors, electrochromic devices, energy storage systems, and catalysis. Its tunable electrical conductivity and stability make it an ideal candidate for emerging technologies such as solid oxide fuel cells and super capacitors.
Co_3O_4 is a prototypical antiferromagnetic material with a rock salt crystal structure. Its magnetic moments align in an antiparallel fashion, resulting in a net zero magnetization. Co_3O_4 has a moderate magnetic moment and relatively high magnetic anisotropy, making it suitable for spintronic applications. It has been extensively studied for its magnetic properties, spin dynamics, and magneto-optical effects (Santos *et al*, 2021).
Cobalt oxide exhibits fascinating physical properties that make it an important material in the field of magnetism and beyond. Its antiferromagnetic behavior, cubic crystal structure, semiconducting nature, and thermal stability offer a plethora of opportunities for scientific exploration

and technological advancements (Vennela et al., 2019). With ongoing research and development, cobalt oxide is poised to contribute significantly to a wide range of applications, benefiting various industries and paving the way for future innovations.

Iron Oxide
Iron oxide is another important magnetic material with a rock salt crystal structure similar to CoO (Navarro *et al.,* 2017). Three oxygen compounds of iron are known: ferrous oxide, FeO; ferric oxide, Fe_2O_3; and ferrosoferric oxide, or ferroferric oxide, Fe_3O_4, which contains iron in both +2 and +3 oxidation states. Ferrous oxide is a greenish to black powder used primarily as a pigment for glasses. It occurs in nature as the mineral wuestite and it can be prepared by heating a ferrous compound in the absence of air or by passing hydrogen over ferric oxide(Morss, 2024). Ferric oxide is a reddish-brown to black powder that occurs naturally as the mineral hematite. It can be produced synthetically by igniting virtually any ferrous compound in air. Ferric oxide is the basis of a series of pigments ranging from yellow to a red known as Venetian red. The finely powdered red form, often called jewelers' rouge, is used for polishing precious metals and diamonds, as well as in cosmetics.

Ferric oxide forms a number of hydrates with variable structures and compositions. A common form is iron rust, produced by the combined action of moisture, carbon dioxide, and oxygen in the air on metallic iron. This process occurs in two steps: first, iron dissolves in the acid solution produced by the moisture and the carbon dioxide of the air, to form ferrous iron and liberate hydrogen; second, oxygen from the air oxidizes the ferrous iron to form hydrated ferric oxide.

Ferrosoferric oxide occurs as the mineral magnetite in the form of magnetic, black or red-black crystals. It is prepared by passing steam over red-hot iron. The oxide is widely employed in ferrites, substances with high magnetic permeability and high electrical resistivity used in certain computer memories and coatings for magnetic tape. It is also used as a pigment and a polishing agent. It exhibits antiferromagnetic ordering below the Néel temperature, which is around 120 K (Gupta, *et al.*, 2005). However, FeO displays additional complexity in its magnetic properties. It undergoes a Verwey transition near 120 K, resulting in a sudden change in its electrical resistivity. Below the Verwey transition temperature, FeO exhibits a unique magnetic and electronic structure, often referred to as a charge ordering state. This transition is associated with the rearrangement of electrons within the crystal lattice, leading to an altered magnetic and transport behavior.

FeO has been extensively studied for its magnetism, charge ordering phenomena, and its potential applications in magnetic storage and sensors. Iron oxide (FeO) is a widely studied magnetic material known for its remarkable physical properties. Delving into the diverse range of physical characteristics exhibited by iron oxide, including its magnetic behavior, crystal structure, electrical conductivity, and thermal properties. Understanding these properties is crucial for harnessing the potential of iron oxide in numerous applications, spanning from magnetic storage to biomedical sensing. Ferromagnetic metals such as iron are extremely well-known (Vennela et al, 2019). In fact, it is the strongest ferromagnetic metal. Our planet receives its magnetic properties from it, and it makes up a substantial part of its core. The Earth therefore functions as a permanent magnet by itself. There are many factors that contribute to iron's magnetism. In addition to its electron spin at the atomic level, its crystalline structure plays an important role as well. In the absence of this, iron would be a non-magnetic metal. Depending on the crystalline structure, iron has different properties. The alpha-FE structure of iron's body-centred cubic (bcc) structure makes it ferromagnetic. Meanwhile, it does not display magnetism in face-centred cubic (fcc) gamma-Fe structures. The beta-Fe structure, for example, exhibits paramagnetic properties.

Magnetic Properties
Iron oxide displays intriguing magnetic behavior, making it an essential material for magnetic applications. It exhibits ferromagnetic properties at low temperatures, meaning that its magnetic moments align in parallel and spontaneous magnetization occurs. However, as the temperature increases, the magnetization decreases until it reaches the Curie temperature (T_C), approximately 1043 K for iron oxide, where it loses its ferromagnetic properties and becomes paramagnetic. This behavior renders iron oxide suitable for applications in magnetic recording, magnetic resonance imaging (MRI), and magnetic sensors (Khan *et al*, 2024).

Crystal Structure
The crystal structure of iron oxide varies depending on its composition. The most common forms include magnetite (Fe_3O_4) and hematite (Fe_2O_3). Magnetite possesses a spinel crystal structure, with iron ions occupying tetrahedral and octahedral sites, while hematite exhibits a corundum crystal structure. The crystal structure significantly influences the magnetic properties and electrical conductivity of iron oxide, making it a subject of intense investigation in the field of materials science.(Kittel, 2004)

Electrical Conductivity
The electrical conductivity of iron oxide is strongly dependent on its crystal structure, composition, and defect concentration. Pure iron oxide, such as hematite, is considered an insulator. However, by introducing defects or doping with appropriate elements, the electrical

conductivity can be enhanced, enabling applications in electronics, electrochemistry, and energy storage devices.

Thermal Properties

Iron oxide demonstrates excellent thermal stability, making it suitable for high-temperature applications. It has a high melting point of approximately 1538°C and exhibits low thermal expansion coefficients. These properties make iron oxide a valuable material for catalysis, thermal barrier coatings, and high-temperature magnetic devices.

Applications

The exceptional physical properties of iron oxide make it highly versatile for a range of applications. In addition to its role in magnetic storage and biomedical imaging, iron oxide finds uses in magnetic nanoparticles for drug delivery and hyperthermia treatments (Kuppan *et al*, 2017). Its electrical conductivity, thermal stability, and catalytic properties also contribute to its application in fuel cells, sensors, and environmental remediation. Iron oxide stands as a captivating magnetic material, offering a wealth of physical properties that make it invaluable for various scientific and technological endeavors. Its magnetic behavior, crystal structure, electrical conductivity, and thermal stability open doors to a multitude of applications, spanning fields such as electronics, medicine, energy, and environmental sciences. As research in iron oxide advances, further exploration of its physical properties is anticipated, leading to new discoveries and innovative applications.

Manganese Oxide

Magnetic materials have garnered significant attention due to their numerous applications in various fields, including data storage, magnetic sensors, and spintronics (Kittel ,2004). Among these materials, manganese oxide (MnO) and its various compounds have emerged as promising candidates. Manganese (II) oxide is actually an inorganic compound, and has the chemical formula MnO. Like many other monoxides, it has a rock salt structure, which means that both the cations and anions are octahedrally coordinated. Fig 2 below is the structure of manganese oxide(Morss , 2024).
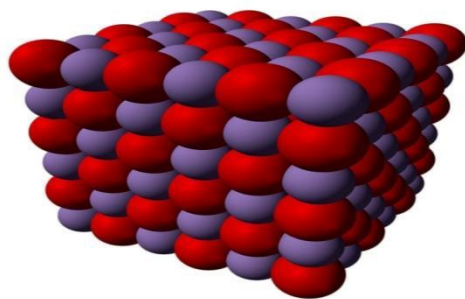

Figure 2: Manganese (II) oxide (Photo Credit : CCoil / Wikimedia Commons)

Manganese oxide is commonly used as fertilizers and food additives. its effectiveness in the fertilizer industry increases its annual consumption which lies in the range of thousands of tons. Moreso, manganese (II) oxide is used as a catalyst in the production of allyl alcohol, paints, colored glass, ceramics etc. An overview of the physical properties of MnO-based magnetic materials, with a focus on their magnetic behavior, crystal structure, and electrical properties is considered(Morss, 2024).

Magnetic Behavior of MnO-based Materials

Manganese oxide exhibits a range of magnetic behaviors depending on its structural phases, including antiferromagnetic, ferromagnetic, and spin glass behavior. The antiferromagnetic phase, known as MnO, is the most well-studied form. MnO possesses a Néel temperature (T_N) of approximately 118K, below which it exhibits antiferromagnetic ordering with a Neél-type antiferromagnetic structure. The magnetic moments of Mn ions align antiparallel to each other within the crystal lattice, resulting in a net magnetization of zero (Yang *et al*, 2002).MnO has a relatively high magnetic moment and displays a strong magnetic anisotropy, making it a suitable candidate for spintronic devices. MnO also exhibits intriguing phenomena such as spin reorientation transitions and magnetic phase transitions under external magnetic fields. It has been extensively studied for its magneto-optical properties, magnetic domain structures, and its applications in magneto-electronics and catalysis. (Qian *et al*, 2019)

Crystal Structure of MnO-based Materials

MnO crystallizes in a rock salt (NaCl) structure, where each Mn^{2+} ion is surrounded by six oxygen ions arranged in an octahedral coordination. The crystal structure plays a crucial role in determining the magnetic properties of MnO-based materials. Substitutions of Mn^{2+} ions by other transition metal ions can alter the magnetic behavior, leading to intriguing phenomena like magnetism-induced Ferro electricity (Kittel, 2004).
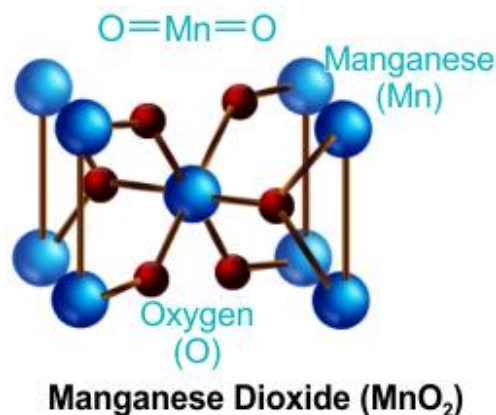
Figure 3: Manganese Dioxide Structure,
(Photo Credit : CCoil / Wikimedia Commons)

Electrical Properties of MnO-based Materials

Apart from their magnetic properties, MnO-based materials exhibit interesting electrical characteristics. For instance, the resistivity of MnO shows a sudden decrease near the antiferromagnetic phase transition, known as a metal-insulator transition. This behavior has been attributed to the suppression of spin fluctuations at low temperatures, resulting in the formation of a charge-ordered state (Kittel, 2004).Similar to CoO and FeO, MnO undergoes a metal-insulator transition near room temperature, where it changes from a high-resistance insulating state to a metallic state. MnO is used in spintronic devices, magneto-optical devices, and as a catalyst due to its unique magnetic and electrical properties (Liu et *al.*, 2024).Manganese oxide (MnO) and its derivatives exhibit intriguing physical properties, particularly in terms of their magnetic behavior, crystal structure, and electrical characteristics (saha *et al.,* (2017)). Understanding and manipulating these properties can open up new avenues for applications in diverse fields.

CONCLUSION

CoO, FeO, and MnO are magnetic materials that possess distinct magnetic properties and behaviors. CoO exhibits antiferromagnetic ordering with high magnetic anisotropy, while FeO undergoes a Verwey transition and exhibits charge ordering phenomena. MnO displays antiferromagnetic behavior with a high magnetic moment and strong magnetic anisotropy. These materials have been extensively studied for their magnetic properties, spin dynamics, and potential applications in various fields such as spintronics, magneto-optics, and catalysis. Understanding the intricate magnetic properties of CoO, FeO, and MnO is crucial for advancing their technological applications and exploring new frontiers in the field of magnetism. Further research is warranted to unravel their underlying mechanisms and to discover novel functionalities in these materials.

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