Magnetism

Lecture 9- 10

Exchange Interaction and Magnetic Crystallization in Solid Materials

Msc. Ali Jaafar

2nd stage

Department of medical physics Al-Mustaqbal University-College

2025- 2026

Magnetic crystallography is the study of the magnetic properties of crystalline materials. Exchange forces—strong quantum interactions arising from the spin of electrons—play a fundamental role in determining the behavior of these materials by aligning the atomic magnetic moment of each electron. This leads to phenomena such as ferromagnetism, ferrimagnetism, and antiferromagnetism. These interactions are what enable a material to become a magnet when the small internal magnetic fields become aligned.

Exchange interaction

What is the exchange interaction?

The exchange interaction stabilises the aligned elementary magnets, i.e. the atomic spins, in magnetic materials. This is the only reason why the parallel alignment of the elementary magnets in ferromagnets is so stable and why the magnetic forces between different magnets or between ferromagnetic iron and a magnet are so strong. The physical cause of the exchange interaction is the Pauli exclusion principle.

The exchange interaction manifests itself as a force that acts between elementary magnets, namely electron spins, in a solid-state body. The exchange interaction is a force that can only be understood through quantum theory and is based on the Pauli principle. It is not directly involved with the magnetic moment of the electron spins and is not simply a force that arises when an elementary magnet in the material exerts magnetic forces on a neighbouring elementary magnet. These magnetic forces would be far too small to explain the strong exchange interaction in ferromagnets. The forces that follow the Pauli exclusion principle can be enormous. These forces are even strong enough to stabilise neutron stars against gravitational collapse. Only the force of a supernova, i.e. an exploding star that leaves behind a black hole, can overcome the forces of the Pauli principle.

Electrons are so-called fermions. According to the Pauli exclusion principle, they cannot be in the same place if they do not differ in any other parameter (such as the direction of the spin, for example). This is what the Pauli exclusion principle states about electrons.

Origin of the exchange interaction

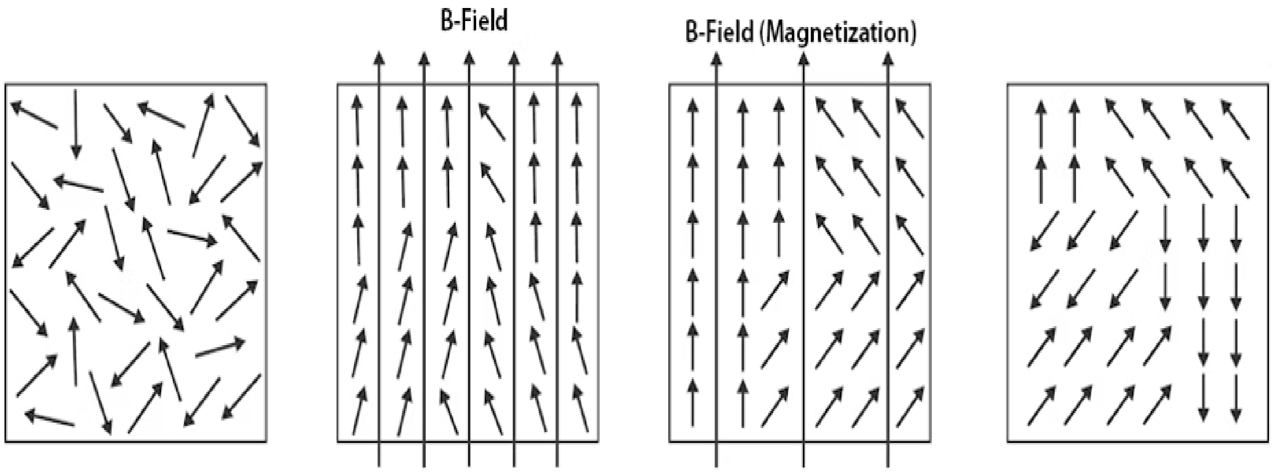
The exchange interaction occurs because the different electron spins in a ferromagnetic material must not differ in the direction of the spin. This is because the Pauli exclusion principle is determined by the symmetry properties of the fermions, i.e. the electrons, which can have different consequences for the orientation of the spin (two electrons in the same space must have opposite spins, whereas two electrons in a ferromagnetic material must not have opposite spins). Just as the Pauli exclusion principle in ferromagnets prohibits the spins of neighbouring electrons from being in opposite directions, a force acts between the electrons to stabilise the parallel position of the spins. This force is called the exchange interaction (see below for details).

Consequences of the exchange interaction

In the following, the consequences of the exchange interaction will be discussed first.
The electron spin carries a magnetic moment. This magnetic moment is aligned by an external magnetic field. If there are unpaired electron spins on the individual atoms in a solid-state body (such as in paramagnets and ferromagnets), a magnetisation of the entire solid object occurs due to a parallel positioning of the magnetic moments of all atoms and because the contributions of all unpaired electron spins in the parallel position add up to a magnetisation of the entire solid object.
In the case of paramagnets, the exchange interaction between the aligned electron spins is much smaller than the thermal energy, i.e. the kinetic energy, of the electrons involved. As a result, the electron spins of a paramagnetic material do not remain permanently aligned at room temperature. In paramagnets, the magnetisation is lost after the external magnetic field is switched off because the stabilisation of the aligned electron spins as a result of the exchange interaction is not greater than the thermal energy of the electrons.
In ferromagnetic materials, however, the magnetisation remains even after the external magnetic field is turned off. Consequently, the exchange interaction in ferromagnets is greater than the thermal energy. A magnetised ferromagnet is not easily demagnetised again. Only heavy impacts, high temperatures above the Curie temperature or an oppositely polarised external magnetic field of coercivity can overcome the exchange interaction of the electron spins and thus the magnetisation.

Phenomenon of Weiss domains

Interestingly, a ferromagnet does not magnetise spontaneously, but the electron spins are aligned within certain areas of the material, whereby the electron spins within such an area are aligned parallel to each other. These areas are called Weiss' domains.



In the image, the magnetic moments of the electron spins are represented by small arrows. Long arrows that extend beyond the boundary of the images indicate a resulting magnetic flux density in the entire material, i.e. a magnetic field. In this case, we speak of a macroscopic flux density. Without an external magnetic field, the spins of a paramagnetic material are randomly orientated (left image). The overall magnetisation is zero. An external magnetic field causes the spins to align, i.e. magnetisation occurs (second image from left). In ferromagnets, the spins are aligned completely parallel in large areas, and part of the magnetisation remains even after the field is switched off, thanks to the exchange interaction (second image from the right). Demagnetisation processes manifest themselves by the fact that the spins start to jumble until the contributions of the individual spins compensate each other. Nevertheless, the spins remain aligned in parallel in large areas (i.e. the Weiss domains) (far right). Often, the alignment of all electron spins in a Weiss domain changes collectively.

The phenomenon of Weiss' domains, which arise due to the exchange interaction, can be illustrated in a macroscopic model. For this purpose, a set of compass needles is mounted on a board so they can freely rotate, and then it is observed how they influence each other. This model also corresponds to the illustration above.

1. **Mechanism of Exchange Forces**

- **Quantum Basis:** Exchange forces are a physical phenomenon that can only be explained using quantum mechanics.
- **Origin:** These forces occur between the elementary magnets (the spin magnetic moments of electrons) within solid materials.
- **Effect:** Exchange forces drive the atomic magnetic moment of an electron to align with the magnetic moments of other atoms in the material.

2. **Effect of Exchange Forces on Magnetic Phenomena**

- **Formation of Magnetism:**

In a non-magnetized material, the tiny magnetic moments of electrons point in random directions and cancel each other out. However, exchange forces arrange these moments so that they all point in the same direction, turning the material into a magnet.

3. **Types of Magnetism:**

Exchange forces give rise to different types of magnetism depending on the orientation of the alignment:

- **Ferromagnetism:** All magnetic moments point in the same direction.
- **Antiferromagnetism:** Magnetic moments align in opposite directions.
- **Ferrimagnetism:** Magnetic moments oppose each other partially.

- **Interactions Between Crystals:**
- When a crystal is placed in a non-uniform magnetic field, it experiences a force that depends on its magnetic nature and the field intensity. This force can be measured to determine the magnetic susceptibility of the crystal.

4. **Importance of Studying Magnetic Crystallography**

- **Understanding Material Behavior:**

Magnetic crystallography helps in understanding the magnetic properties of crystalline materials, including how these properties form and how they behave in different magnetic fields.

- **Technological Applications:**

Understanding quantum magnetic mechanisms is essential for developing new technologies in fields such as microelectronics, magnetic data storage, and magnetic sensing devices.

5. **Forces Between Magnets**

Magnets exert forces and torques on each other according to electromagnetic laws. The attractive magnetic forces originate from microscopic electric currents of electrons orbiting nuclei and from the intrinsic magnetism of fundamental particles (like electrons). Well-established models describe these phenomena, in which tiny current loops—called magnetic dipoles—produce their own magnetic fields and respond to external ones. Therefore, the fundamental force between magnets is the interaction of magnetic dipoles.

If all dipoles that compose two magnets are known, the total force on each magnet can be determined by summing the interactions between dipoles in one magnet and those in the other. A common and effective simplification is to model the interaction as occurring between "magnetic charges" smeared over the poles of the magnets. These magnetic charges are always connected by a thread of magnetized material, and isolated magnetic charges do not exist. This model works well for predicting forces between simple magnets where the distribution of "magnetic charge" is known.

6. **Magnetic Poles vs. Atomic Currents**

The magnetic field of a magnet is the result of all the fields generated by its magnetized volume elements, which consist of tiny atomic magnetic dipoles. Directly summing the fields of all these dipoles requires a three-dimensional integral—even for a single magnet—which can be complicated.

In cases of uniform magnetization, the problem can be simplified in two distinct ways using Stokes' theorem:

- When integrating along the magnetization direction, the dipoles along the integration path cancel out except at the magnet's end surfaces. Thus, the field appears to originate from magnetic charges distributed on the ends of the magnet—this is the **Gilbert model**.
- When integrating over a surface perpendicular to the magnetization, the dipoles cancel except at the outer surface, reducing the model to a loop current—this is the **Ampère model**.

Both models reduce the problem to considering two-dimensional surface distributions, which is simpler than the original three-dimensional task.

7. Ampère Model

In the Ampère model, magnetization arises from microscopic circular bound currents—called Ampèrian currents—circulating within the material. The combined effect of these currents makes the magnet behave as if there were macroscopic electric currents flowing in loops inside it, with the magnetic field perpendicular to these loops. The field is then obtained using the Biot–Savart law. The Ampère model gives the correct magnetic flux density **B** inside and outside the magnet, although calculating surface currents can sometimes be difficult.

8. Gilbert Model

In the Gilbert model, the polar surfaces of a permanent magnet are imagined to be covered with so-called magnetic charges: north-pole particles at the north pole and south-pole particles at the south pole. These act as the sources of magnetic field lines. The field is obtained similarly to Coulomb's law but using magnetic instead of electric charges. If the distribution of magnetic poles is known, the model gives the exact field intensity **H** inside and outside the magnet. The charges are uniformly distributed if the magnet is uniformly magnetized with flat sides (e.g., a cylinder or prism). This is known as the Gilbert model of magnetic dipoles.

9. Magnetic Dipole Moment

Far from a magnet, the magnetic field (to a good approximation) resembles that of a dipole characterized by the total magnetic dipole moment **m**. This is valid regardless of the magnet's shape as long as its net magnetic moment is nonzero. A dipole field has the property that the field strength decreases inversely with the cube of the distance from the magnet's center.

Therefore, the magnetic moment of a magnet is a measure of its strength and orientation. Magnetic moments also exist for current loops, bar magnets, electrons, molecules, and even planets. More precisely, the term "magnetic moment" typically refers to the dipole magnetic moment of the system, which is the leading term in the multipole expansion of the magnetic field. Both the torque and the force exerted by an external magnetic field on a magnet are proportional to its magnetic moment. The magnetic moment is a vector: it has both magnitude and direction. Its direction is from the south pole to the north pole **inside** the magnet. For example, the direction of the magnetic moment of a bar magnet—like that found in a compass—is the direction in which its north pole points.

- In the physically correct Ampère model, the magnetic dipole moment arises from extremely small current loops. The magnetic dipole moment of a small current loop with current **I** and area **A** is:

$$\vec{m} = I\,\vec{A}$$

The direction of **m** is perpendicular to the area according to the right-hand rule. Its SI unit is ampere-square-meter ($A \cdot m^2$). For multi-turn coils, the unit becomes ampere-turn-square-meter.

- In the Gilbert model, the dipole moment is produced by two equal and opposite magnetic charges separated by a distance **d**, analogous to an electric dipole:

$$m = q_m d$$

The direction of the dipole moment is from the negative (south) magnetic charge to the positive (north) magnetic charge.

10. Magnetic Force in a Non-Uniform Magnetic Field

Magnets are drawn along the gradient of a magnetic field. The simplest example is the attraction between opposite poles of two magnets. Each magnet produces a field that becomes stronger near its poles. When opposite poles face each other, each magnet is pulled toward the stronger field near the other magnet's pole. If like poles face each other, they repel and are pushed away from the region of stronger magnetic field.The Gilbert model predicts the correct mathematical form of this force and is easier to understand qualitatively. If a magnet is placed in a uniform magnetic field, both poles experience equal and opposite forces because they have opposite magnetic charges—so the net force is zero. But when placed in a non-uniform field (such as the field of another magnet), the pole in the stronger field experiences a greater force, resulting in a net force on the entire magnet. If two magnets are aligned in the same direction and brought near each other by their opposite poles, they are attracted toward the region of stronger magnetic field. If they are aligned oppositely—like poles facing each other—they are pushed away from the region of stronger magnetic field.