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FERROMAGNETISM

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Abstract

Ferromagnetism is the basic mechanism by which certain materials (such as iron) form permanent magnets, or are attracted to magnets. In physics, several different types of magnetism are distinguished. Ferromagnetism (including ferrimagnetism) is the strongest type; it is the only type that creates forces strong enough to be felt, and is responsible for the common phenomena of magnetism encountered in everyday life. Other substances respond weakly to magnetic fields with two other types of magnetism, paramagnetism and diamagnetism, but the forces are so weak that they can only be detected by sensitive instruments in a laboratory. An everyday example of ferromagnetism is a refrigerator magnet used to hold notes on a refrigerator door. The attraction between a magnet and ferromagnetic material is "the quality of magnetism first apparent to the ancient world, and to us today".

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Permanent magnets (materials that can be magnetized by an external magnetic fieldand remain magnetized after the external field is removed) are either ferromagnetic or ferrimagnetic, as are other materials that are noticeably attracted to them. Only a few substances are ferromagnetic. The common ones are iron, nickel, cobalt and most of their alloys, some compounds of rare earth metals, and a few naturally-occurring minerals such as lodestone.

Ferromagnetism is very important in industry and modern technology, and is the basis for many electrical and electromechanical devices such as electromagnets, electric motors, generators, transformers, and magnetic storage such as tape recorders, and hard disks.

History and distinction from ferrimagnetism

Historically, the term ferromagnet was used for any material that could exhibit spontaneous magnetization: a net magnetic moment in the absence of an external magnetic field. This general definition is still in common use. More recently, however, different classes of spontaneous magnetization have been identified when there is more than one magnetic ion per primitive cell of the material, leading to a stricter definition of "ferromagnetism" that is often used to distinguish it from ferrimagnetism. In particular,

- A material is "ferromagnetic" in this narrower sense only if all of its magnetic ions add a positive contribution to the net magnetization.
- If some of the magnetic ions subtract from the net magnetization (if they are partially anti-aligned), then the material is "ferrimagnetic".

High-Temperature Weak Ferromagnetism in a Low-Density Free-Electron Gas

The magnetic properties of the ground state of a low-density free-electron gas in three dimensions have been the subject of theoretical speculation and controversy for seven decades1. Not only is this a difficult theoretical problem to solve, it is also a problem which has not hitherto been directly addressed experimentally. Here we report measurements on electron-doped calcium hexaboride (CaB6) which, we argue, show that—at a density of 7 1019 electrons cm-3—the ground state is ferromagnetically polarized with a saturation moment of 0.07 Bper electron. Surprisingly, the magnetic ordering temperature of this itinerant ferromagnet is 600 K, of the order of the Fermi temperature of the electron gas.

- If the moments of the aligned and anti-aligned ions balance completely so as to have zero net magnetization, despite the magnetic ordering, then it is an antiferromagnet. These alignment effects only occur at temperatures below a certain critical temperature, called the Curie temperature (for ferromagnets and ferrimagnets) or the Néel temperature (for antiferromagnets).

Among the first investigations of ferromagnetism are the pioneering works of Aleksandr Stoletov on measurement of the magnetic permeability of ferromagnetics, known as the Stoletov curve.

Ferromagnetic materials

Curie temperatures for some crystalline ferromagnetic (* = ferrimagnetic) materials	
Material	**Curie temp. (K)**
Co	1388
Fe	1043
$Fe_2O_3^*$	948
$FeOFe_2O_3^*$	858
$NiOFe_2O_3^*$	858
$CuOFe_2O_3^*$	728
$MgOFe_2O_3^*$	713
MnBi	630
Ni	627
MnSb	587
$MnOFe_2O_3^*$	573

$Y_3Fe_5O_{12}$	560
CrO_2	386
MnAs	318
Gd	292
Dy	88
EuO	69

The table on the right lists a selection of ferromagnetic and ferrimagnetic compounds, along with the temperature above which they cease to exhibit spontaneous magnetization (see Curie temperature).

Ferromagnetism is a property not just of the chemical make-up of a material, but of its crystalline structure and microscopic organization. There are ferromagnetic metal alloys whose constituents are not themselves ferromagnetic, called Heusler alloys, named after Fritz Heusler. Conversely there are non-magnetic alloys, such as types of stainless steel, composed almost exclusively of ferromagnetic metals.

One can also make amorphous (non-crystalline) ferromagnetic metallic alloys by very rapidquenching (cooling) of a liquid alloy. These have the advantage that their properties are nearly isotropic (not aligned along a crystal axis); this results in low coercivity, low hysteresis loss, high permeability, and high electrical resistivity. One such typical material is a transition metal-metalloid alloy, made from about 80% transition metal (usually Fe, Co, or Ni) and a metalloid component (B,C, Si, P, or Al) that lowers the melting point.

A relatively new class of exceptionally strong ferromagnetic materials are the rare-earth magnets. They contain lanthanide elements that are known for their ability to carry large magnetic moments in well-localized f-orbitals.

Actinide ferromagnets

A number of actinide compounds are ferromagnets at room temperature or become ferromagnets below the Curie temperature (TC). PuP is one actinide pnictide that is a paramagnet and hascubic symmetry at room temperature, but upon cooling undergoes a lattice distortion to tetragonalwhen cooled to below its Tc = 125 K. PuP has an easy axis of <100>,so that at 5 K.[6] The lattice distortion is presumably a consequence of strain induced by the magnetoelastic interactions as the magnetic moments aligned parallel within magnetic domains.

In NpFe2 the easy axis is <111>. Above TC ~500 K NpFe2 is also paramagnetic and cubic. Cooling below the Curie temperature produces a rhombohedral distortion wherein the rhombohedral angle changes from 60° (cubic phase) to 60.53°. An alternate description of this distortion is to consider the length c along the unique trigonal axis (after the

distortion has begun) and a as the distance in the plane perpendicular to c. In the cubic phase this reduces to = 1.00. Below the Curie temperature which is the largest strain in any actinide compound.[6] NpNi2 undergoes a similar lattice distortion below TC = 32 K, with a strain of (43 ± 5) × 10−4.[6] NpCo2 is a ferrimagnet below 15 K.

Lithium gas

In 2009, a team of MIT physicists demonstrated that a lithium gas cooled to less than one kelvin can exhibit ferromagnetism. The team cooled fermionic lithium-6 to less than 150 billionths of one kelvin above absolute zero using infrared laser cooling. This demonstration is the first time that ferromagnetism has been demonstrated in a gas.

Explanation

The Bohr–van Leeuwen theorem shows that magnetism cannot occur in purely classical solids. Without quantum mechanics, there would be no diamagnetism, paramagnetism or ferromagnetism. The property of ferromagnetism is due to the direct influence of two effects from quantum mechanics: spin and the Pauli exclusion principle.

Origin of magnetism

One of the fundamental properties of an electron (besides that it carries charge) is that it has a magnetic dipole moment, i.e., it behaves itself as a tiny magnet. This dipole moment comes from the more fundamental property of the electron that it has quantum mechanical spin. The quantum mechanical nature of this spin causes the electron to only be able to be in two states, with the magnetic field either pointing "up" or "down" (for any choice of up and down). The spin of the electrons in atoms is the main source of ferromagnetism, although there is also a contribution from the orbital angular momentum of the electron about the nucleus. When these tiny magnetic dipoles are aligned in the same direction, their individual magnetic fields add together to create a measurable macroscopic field.

However, in materials with a filled electron shell, the total dipole moment of the electrons is zero because the spins are in up/down pairs. Only atoms with partially filled shells (i.e., unpaired spins) can have a net magnetic moment, so ferromagnetism only occurs in materials with partially filled shells. Because of Hund's rules, the first few electrons in a shell tend to have the same spin, thereby increasing the total dipole moment.

These unpaired dipoles (often called simply "spins" even though they also generally include angular momentum) tend to align in parallel to an external magnetic field, an effect called paramagnetism. Ferromagnetism involves an additional phenomenon, however: The dipoles tend to align spontaneously, giving rise to a spontaneous magnetization, even when there is no applied field.

Exchange interaction

According to classical electromagnetism, two nearby magnetic dipoles will tend to align in opposite directions, so their magnetic fields will oppose one another and cancel out. However, this effect is very weak, because the magnetic fields generated by individual spins are small and the resulting alignment is easily destroyed by thermal fluctuations. In a few materials, a much stronger interaction between spins arises because the change in the direction of the spin leads to a change in electrostatic repulsion between neighboring electrons, due to a particular quantum mechanical effect called theexchange interaction. At short distances, the exchange interaction is much stronger than the magnetic dipole-dipole interaction. As a result, in a few materials, the ferromagnetic ones, nearby spins tend to align in the same direction. In certain doped semiconductor oxides RKKY interactions have been shown to bring about periodic longer-range magnetic interactions, a phenomenon of significance in the study of spintronic materials.

The exchange interaction is related to the Pauli exclusion principle, which says that two electrons with the same spin cannot also have the same "position". Therefore, under certain conditions, when the orbitals of the unpaired outer valence electrons from adjacent atoms overlap, the distributions of their electric charge in space are further apart when the electrons have parallel spins than when they have opposite spins. This reduces the electrostatic energy of the electrons when their spins are parallel compared to their energy when the spins are anti-parallel, so the parallel-spin state is more stable. In simple terms, the electrons, which repel one another, can move "further apart" by aligning their spins, so the spins of these electrons tend to line up. This difference in energy is called the exchange energy.

The materials in which the exchange interaction is much stronger than the competing dipole-dipole interaction are frequently called magnetic materials. For instance, in iron (Fe) the exchange force is about 1000 times stronger than the dipole interaction. Therefore below the Curie temperature virtually all of the dipoles in a ferromagnetic material will be aligned. The exchange interaction is also responsible for the other types of spontaneous ordering of atomic magnetic moments occurring in magnetic solids, antiferromagnetism and ferrimagnetism. There are different exchange interaction mechanisms which create the magnetism in different ferromagnetic, ferrimagnetic, and antiferromagnetic substances. These mechanisms include direct exchange, RKKY exchange, double exchange, and superexchange.

Magnetic anisotropy

Although the exchange interaction keeps spins aligned, it does not align them in a particular direction. Without magnetic anisotropy, the spins in a magnet randomly change

direction in response to thermal fluctuations and the magnet issuperparamagnetic. There are several kinds of magnetic anisotropy, the most common of which is magnetocrystalline anisotropy. This is a dependence of the energy on the direction of magnetization relative to the crystallographic lattice. Another common source of anisotropy, inverse magnetostriction, is induced by internal strains. Single-domain magnets also can have a shape anisotropy due to the magnetostatic effects of the particle shape. As the temperature of a magnet increases, the anisotropy tends to decrease, and there is often a blocking temperature at which a transition to superparamagnetism occurs.

Ferromagnetic materials spontaneously divide into magnetic domains because theexchange interaction is a short-range force, so over long distances of many atoms the tendency of the magnetic dipoles to reduce their energy by orienting in opposite directions wins out. If all the dipoles in a piece of ferromagnetic material are aligned parallel, it creates a large magnetic field extending into the space around it. This contains a lot of magnetostatic energy. The material can reduce this energy by splitting into many domains pointing in different directions, so the magnetic field is confined to small local fields in the material, reducing the volume of the field. The domains are separated by thin domain walls a number of molecules thick, in which the direction of magnetization of the dipoles rotates smoothly from one domain's direction to the other.

Magnetized materials

Thus, a piece of iron in its lowest energy state ("unmagnetized") generally has little or no net magnetic field. However, if it is placed in a strong enough external magnetic field, the domain walls will move, reorienting the domains so more of the dipoles are aligned with the external field. The domains will remain aligned when the external field is removed, creating a magnetic field of their own extending into the space around the material, thus creating a "permanent" magnet. The domains do not go back to their original minimum energy configuration when the field is removed because the domain walls tend to become 'pinned' or 'snagged' on defects in the crystal lattice, preserving their parallel orientation. This is shown by the Barkhausen effect: as the magnetizing field is changed, the magnetization changes in thousands of tiny discontinuous jumps as the domain walls suddenly "snap" past defects.

This magnetization as a function of the external field is described by a hysteresis curve. Although this state of aligned domains found in a piece of magnetized ferromagnetic material is not a minimal-energy configuration, it is metastable, and can persist for long periods, as shown by samples of magnetite from the sea floor which have maintained their magnetization for millions of years.

Alloys used for the strongest permanent magnets are "hard" alloys made with many defects in their crystal structure where the domain walls "catch" and stabilize. The net

magnetization can be destroyed by heating and then cooling (annealing) the material without an external field, however. The thermal motion allows the domain boundaries to move, releasing them from any defects, to return to their low-energy unaligned state.

Curie temperature

As the temperature increases, thermal motion, or entropy, competes with the ferromagnetic tendency for dipoles to align. When the temperature rises beyond a certain point, called the Curie temperature, there is a second-order phase transitionand the system can no longer maintain a spontaneous magnetization, although it still responds paramagnetically to an external field. Below that temperature, there is a spontaneous symmetry breaking and magnetic moments become aligned with their neighbors. The Curie temperature itself is a critical point, where the magnetic susceptibility is theoretically infinite and, although there is no net magnetization, domain-like spin correlations fluctuate at all length scales.

The study of ferromagnetic phase transitions, especially via the simplified Ising spin model, had an important impact on the development of statistical physics. There, it was first clearly shown that mean field theory approaches failed to predict the correct behavior at the critical point (which was found to fall under a universality class that includes many other systems, such as liquid-gas transitions), and had to be replaced by renormalization group theory.

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