Four Different Kinds of Magnetism

1.) Diamagnetism

A phenomenon in some materials in which the susceptibility is negative, i.e. the magnetization opposed the magnetizing force. It arises from the precession of spinning charges in a magnetic field.

The magnetization is in the ***opposite*** direction to that of the applied field, i.e. the magnetic susceptibility is negative ($\chi_m < 0$). Although ***all*** substances are diamagnetic, it is a weak form of magnetism and may be masked by other, stronger forms. Diamagnetism results from changes induced in the orbits of electrons in the atoms of a substance by the applied field, the direction of change (in accordance with Lenz's law) opposing the applied magnetic flux. There is thus a weak negative susceptibility ($\chi_m < 0$) and a relative magnetic permeability of slightly less than one (i.e. $\mu_r = \mu / \mu_o = (1 + \chi_m) < 1$).

Diamagnetism is a very weak form of magnetism that is only exhibited in the presence of an external magnetic field. It is the result of changes in the orbital motion of electrons due to the external magnetic field. The induced magnetic moment is very small and in a direction opposite to that of the applied field. When placed between the poles of a strong electromagnet, diamagnetic materials are attracted towards regions where the magnetic field is weak. Diamagnetism is found in all materials; however, because it is so weak it can only be observed in materials that do not exhibit other forms of magnetism. Also, diamagnetism is found in elements with paired electrons. Oxygen was once thought to be diamagnetic, but a new revised molecular orbital (MO) model confirmed oxygen's paramagnetic nature.

An exception to the "weak" nature of diamagnetism occurs with the rather large number of materials that become superconducting, something that usually happens at lowered temperatures. Superconductors are perfect diamagnets and when placed in an external magnetic field expel the field lines from their interiors (depending on field intensity and temperature). Superconductors also have zero electrical resistance, a consequence of their diamagnetism. Superconducting structures have been known to tear themselves apart with astonishing force in their attempt to escape an external field. Superconducting magnets are the major component of most magnetic resonance imaging systems, perhaps the only important application of diamagnetism.

Perhaps the substance that displays the strongest diamagnetism is bismuth, which is used in guns. Melting down bismuth and then molding it is a very efficient way of capturing the diamagnetic properties.

A thin slice of pyrolytic graphite, which is an unusually strongly diamagnetic material, can be stably floated on a magnetic field, such as that from rare earth permanent magnets. This can be done with all components at room temperature, making a visually effective demonstration of diamagnetism.

The Radboud University Nijmegen has conducted experiments where they have successfully levitated water and a live frog. [1] (*http://www.hfml.sci.kun.nl/froglev.html*)

Diamagnetic materials have a relative magnetic permeability that is less than 1, and a magnetic susceptibility that is less than 0. (i.e. $\mu_r = \mu / \mu_o = (1 + \chi_m) < 1$ and $\chi_m < 0$).

Diamagnetism was discovered and named in September 1845 by Michael Faraday.

2.) Paramagnetism

In paramagnetism, the atoms or molecules of the substance have net orbital or spin magnetic moments that are capable of being aligned in the direction of the applied field. They therefore have a positive (but small) susceptibility and a relative permeability slightly in excess of one. Paramagnetism occurs in all atoms and molecules with unpaired electrons; e.g. free atoms, free radicals, and compounds of transition metals containing ions with unfilled electron shells. It also occurs in metals as a result of the magnetic moments associated with the spins of the conducting electrons.

Paramagnetism is the tendency of the atomic magnetic dipoles, due to quantum-mechanical spin angular momentum, in a material that is otherwise non-magnetic to align with an external magnetic field. This alignment of the atomic dipoles with the magnetic field tends to strengthen it, and is described by a relative magnetic permeability, μ_r greater than unity (or, equivalently, a small positive magnetic susceptibility greater than zero), i.e. (i.e. $\mu_r = \mu / \mu_o = (1 + \chi_m) > 1$ and $\chi_m > 0$).

In pure paramagnetism, the external magnetic field acts on each atomic dipole independently and there are no interactions between individual atomic dipoles. Such paramagnetic behavior can also be observed in ferromagnetic materials that are above their Curie temperature.

Paramagnetic materials attract and repel like normal magnets when subject to a magnetic field. Under relatively low magnetic field saturation when the majority of the atomic dipoles are not aligned with the field, paramagnetic materials exhibit magnetization according to **Curie's Law**: $\mathbf{M} = C \cdot \mathbf{B}/T$, where

M is the resulting magnetization (magnetic dipole moment/unit volume), measured in Amps/meter.
B is the magnetic flux density of the applied field, measured in Teslas.
T is absolute temperature, measured in Kelvins.
C is a material-specific Curie constant

This law indicates that paramagnetic materials tend to become increasingly magnetic as the applied magnetic field is increased, but less magnetic as temperature is increased. Curie's law is incomplete because it fails to predict what will happen when most of the little magnets are aligned (after everything is aligned, increasing the external field will not increase the total magnetization) so Curie's Constant really should be expressed as a function of how much of the material is already aligned.

Paramagnetic materials in magnetic fields will act like magnets but when the field is removed, thermal motion will quickly disrupt the magnetic alignment. In general paramagnetic effects are small (magnetic susceptibility of the order of $\chi_m \sim 10^{-3}$ to 10^{-5}).

Ferromagnetic materials above the Curie temperature become paramagnetic.

Paramagnetic Materials

- Aluminum
- Barium
- Calcium
- Liquid Oxygen
- Platinum
- Sodium
- Strontium
- Uranium

3.) Ferromagnetism

A phenomenon in some magnetically ordered materials in which there is a bulk magnetic moment and the magnetization is large. The electron spins of the atoms in the microscopic regions, domains, are aligned. In the presence of an external magnetic field the domains oriented favorably with respect to the field grow at the expense of the others and the magnetization of the domains tends to align with the field.

Above the Curie temperature, the thermal motion is sufficient to offset the aligning force and the material becomes paramagnetic. Certain elements (iron, nickel and cobalt), and alloys with other elements (titanium, aluminium) exhibit relative magnetic permeabilities up to 104 (ferromagnetic materials). Some show marked hysteresis and are used for permanent magnets, magnetic amplifiers etc. In ferromagnetic substances, within a certain temperature range, there are net atomic magnetic moments, which line up in such a way that magnetization persists after the removal of the applied field.

Below a certain temperature, called the Curie point (or Curie temperature) an increasing magnetic field applied to a ferromagnetic substance will cause increasing magnetization to a high value called the saturation magnetization. This is because a ferromagnetic substance consists of small magnetized regions called domains. The total magnetic moment of a sample of the substance is the vector sum of the magnetic moments of the component domains.

Ferromagnetism is a phenomenon by which a material can exhibit a spontaneous magnetization, and is one of the strongest forms of magnetism. It is responsible for most of the magnetic behavior encountered in everyday life, and is the basis for all permanent magnets (as well as the metals that are noticeably attracted to them).

Ferromagnetic materials

There are a number of crystalline materials that exhibit ferromagnetism. We list a representative selection of them here (Kittel, p. 449), along with their Curie temperatures, the temperature above which they cease to be ferromagnetic (see right hand table - A selection of crystalline ferromagnetic materials, along with their Curie temperatures in kelvins (K).)

Material	Curie temp. (K)
Fe	1043
Co	1388
Ni	627
Gd	292
Dy	88
MnAs	318
MnBi	630
MnSb	587
CrO_2	386
$MnOFe_2O_3$	573
$FeOFe_2O_3$	858
$NiOFe_2O_3$	858
$CuOFe_2O_3$	728
$MgOFe_2O_3$	713
EuO	69
$Y_3Fe_5O_{12}$	560

One can also make amorphous (non-crystalline) ferromagnetic metallic alloys by very rapid quenching (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. A typical such 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.

One example of such an amorphous alloy is $Fe_{80}B_{20}$ (Metglas 2605) which has a Curie temperature of 647 K and a room-temperature (300 K) saturation magnetization of 125.7 milliteslas (1257 gauss), compared with 1043 K and 170.7 mT (1707 gauss) for pure iron from above. The melting point, or more precisely the glass transition temperature, is only 714 K for the alloy versus 1811 K for pure iron.

Physical origin

The property of ferromagnetism is due to the direct influence of two effects from quantum mechanics: spin and the Pauli Exclusion Principle.

The intrinsic spin angular momentum of an electron has a magnetic dipole moment associated with it, and it creates a magnetic dipole field. (The classical analog of quantum-mechanical spin is a spinning ball of charge, however the quantum version has distinct differences, such as the fact that it has discrete up/down states that are not described by a vector.) In many materials (specifically those with a filled electron shell), the electrons come in pairs of opposite spin, which cancel one another's dipole moments. Only atoms with unpaired electrons (partially filled shells) can experience a net magnetic moment from spin. A ferromagnetic material has many such electrons, and if they are aligned they create a measurable macroscopic field.

The spins/dipoles tend to align in parallel to an external magnetic field, an effect called paramagnetism. (A similar effect due to the orbital motion of the electrons, which effectively forms a microscopic current loop that also has a magnetic dipole moment, is called diamagnetism.) Ferromagnetism involves an additional phenomenon, however: the spins tend to *align spontaneously*, without any applied field. This is a purely quantum-mechanical effect.

According to classical electromagnetism, two nearby magnetic dipoles will tend to align in *opposite* directions (which would create an antiferromagnetic material). In a ferromagnet, however, they tend to align in the *same* direction because of the Pauli principle: two electrons with the same spin cannot lie at the same position, and thus feel an effective additional repulsion that lowers their electrostatic energy. This difference in energy is called the *exchange energy* and induces nearby electrons to align.

At long distances (after many thousands of ions), the exchange energy advantage is overtaken by the classical tendency of dipoles to anti-align. This is why, in an equilibriated (non-magnetized) ferromagnetic material, the spins in the whole material are not aligned. Rather, they organize into *domains* that are aligned (magnetized) at short range, but at long range adjacent domains are anti-aligned. The transition between two domains, where the magnetization flips, is called a Bloch wall, and is a gradual transition on the atomic scale (covering a distance of about 300 ions for iron).

Thus, an ordinary piece of iron generally has little or no net magnetic moment. However, if it is placed in a strong enough external magnetic field, the domains will re-orient in parallel with that field, and will remain re-oriented when the field is turned off, thus creating a "permanent" magnet. This magnetization as a function of the external field is described by a hysteresis curve. Although this state of aligned domains is not a minimal-energy configuration, it is extremely stable and has been observed to persist for millions of years in seafloor magnetite aligned by the Earth's magnetic field (whose poles can thereby be seen to flip at long intervals). The net magnetization can be destroyed by heating and then cooling (*annealing*) the material without an external field, however.

As the temperature increases, thermal oscillation, or entropy, competes with the ferromagnetic tendency for spins to align. When the temperature rises beyond a certain point, called the **Curie temperature**, there is a second-order phase transition and 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 random domains form (in the absence of an external field). 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.

Unusual Ferromagnetism

In 2004, it was discovered that a certain allotrope of carbon, nanofoam, exhibited ferromagnetism. The effect dissipates after a few hours at room temperature, but lasts longer at cold temperatures. The material is also a semiconductor. It is thought that other similarly formed materials, of boron and nitrogen, may also be ferromagnetic.

4.) Antiferromagnetism

Phenomenon in some magnetically ordered materials in which there is an anti-parallel alignment of spins in two interpenetrating structures so that there is no overall bulk spontaneous magnetization.

In ferromagnetic materials, it is energetically favorable for the spins atomic to align, leading to spontaneous magnetization. However, in antiferromagnetic materials, the conditions are such that it is energetically favorable for the spins to oppose, leading to no overall magnetization

In materials that exhibit **antiferromagnetism**, the spins of magnetic electrons align in a regular pattern with neighboring spins pointing in opposite directions. This is the opposite of ferromagnetism. Generally, antiferromagnetic materials exhibit antiferromagnetism at a low temperature, and become disordered above a certain temperature; the transition temperature is called the Néel temperature. Above the Néel temperature, the material is typically paramagnetic.

The antiferromagnetic behaviour at low temperature usually results in diamagnetic properties, but can sometimes display ferrimagnetic behaviour, which in many physically observable properties are more similar to ferromagnetic interactions.

The magnetic susceptibility, χ_m of an antiferromagnetic material will appear to go through a maximum as the temperature is lowered; in contrast, that of a paramagnet will continually increase with decreasing temperature.

Antiferromagnetic materials have a negative coupling between adjacent moments and low frustration.

Antiferromagnetic materials are relatively uncommon. An example is the heavy-fermion superconductor URu_2Si_2. There are also numerous examples among high nuclearity metal clusters.

Antiferromagnetism, also known as Ferrimagnetism is a property exhibited by materials whose atoms or ions tend to assume an ordered but nonparallel arrangement in zero applied field below a certain characteristic temperature known as the Néel temperature. In the usual case, within a magnetic domain, a substantial net magnetization results from the antiparallel alignment of neighboring nonequivalent sublattices. The macroscopic behavior is similar to ferromagnetism. Above the Néel temperature, these substances become paramagnetic.