Magnetism

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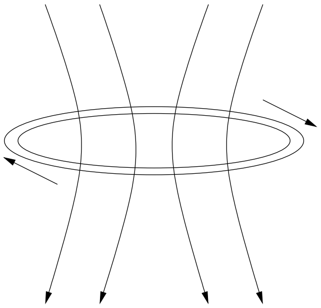
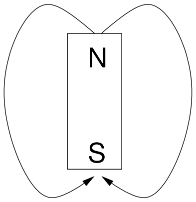
Some basics:

A *magnet* is associated with magnetic lines of force, and a north pole and a south pole. The lines of force come out of the north pole (the source) and are pulled in to the south pole (the sink). A current in a ring or coil also produces magnetic lines of force.





The magnetic dipole (a north-south pair) is usually represented by an arrow. Magnetic fields act on these dipoles and tend to align them.

The magnetic field strength H generated by N closely spaced turns in a coil of wire carrying a current I, for a coil length of l is given by:

$$H = \frac{NI}{l}$$

The units of H are ampères per meter (Am^{-1}) in SI units or oersted (Oe) in CGS. 1 $\mathrm{Am}^{-1} = 4\pi \times 10^{-3}$ Oe.

If a coil (or solenoid) encloses a vacuum, then the magnetic flux density B generated by a field strength H from the solenoid is given by

$$B = \mu_0 H$$

where μ_0 is the vacuum permeability. In SI units, $\mu_0 = 4\pi \times 10^{-7}$ H/m. If the solenoid encloses a medium of permeability μ (instead of the vacuum), then the magnetic flux density is given by:

$$B = \mu H \quad \text{and} \quad \mu = \mu_r \mu_0$$

μ_r is the relative permeability.

Materials respond to a magnetic field by developing a magnetization M which is the number of magnetic dipoles per unit volume.

The magnetization is obtained from:

$$B = \mu_0 H + \mu_0 M$$

The second term, $\mu_0 M$ is reflective of how certain materials can actually concentrate or repel the magnetic field lines. The response of a material to the magnetic field is called the magnetic susceptibility χ defined:

$$\chi = M/H \quad \text{or} \quad M = \chi H$$

χ is unitless and is related to the relative permeability according to $\chi = \mu_r - 1$

The origins of magnetism:

Magnetism arises from the magnetic moment associated with single electrons and their quantum mechanical behavior (electrons have a magnetic and spin quantum numbers). The magnetic moment of individual electrons is $\pm\mu_\mathrm{B}$ (+ or − depending on whether the spin is up or down) where μ_B is the Bohr magneton. $1\ \mu_\mathrm{B} = 9.27 \times 10^{-24}\ \mathrm{Am}^{-1}$.

In a normal paramagnet, all the spins are non-interacting. At any finite temperature, there is a tendency for the spins to misalign, even in the presence of a magnetic field. Only at 0 K do the spins all line up in the presence of a magnetic field, and the magnetic *susceptibility* $\chi = M/H$ *diverges*. M is the magnetization, the number of magnetic dipoles formed per unit volume of sample, and H is the magnetic field. Divergence of the susceptibility arises when even an infinitessimally small field aligns all the spins. The system obeys the Curie law, and is called a Curie paramagnet, with:

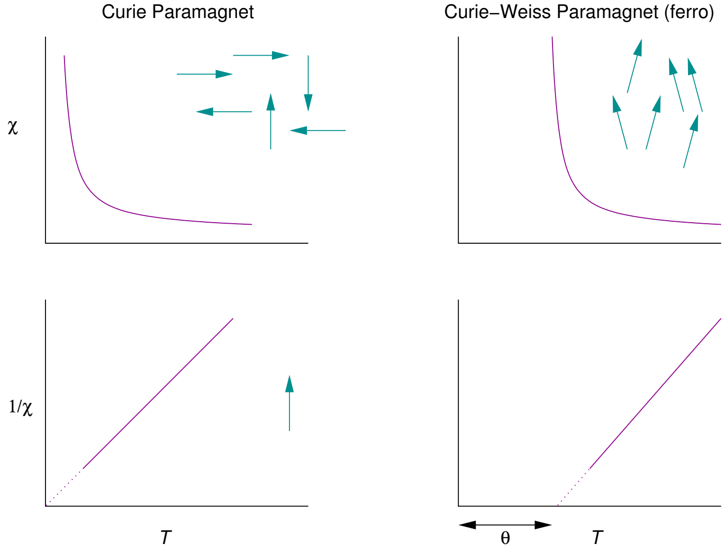
$$\chi = \frac{C}{T}$$

The Curie constant C is indicative of the number of magnetic spins per atom. Good examples of paramagnets are those containing magnetic ions in insulating solids[1] where the ions are far from one another. An example is the alum, $(\mathrm{NH_4})\mathrm{Cr}(\mathrm{SO_4})_2{\cdot}12\mathrm{H_2O}$, where the large number of water molecules in the crystal help isolate the magnetic Cr^{3+} ions.

Ferromagnetic interactions between spins arise as a result of an internal field (the Weiss field). A system that is normally a paramagnet with ferromagnetic interactions, displays, as a result of the internal field, Curie-Weiss behavior in the paramagnetic regime:

$$\chi = \frac{C}{(T-\theta)}$$

As a result of the internal field tending to align the spins, the susceptibility diverges even at finite temperatures. The temperature at which the divergence occurs is called the Weiss constant θ and it is often (but not necessarily) the Curie temperature T_C for the paramagnetic to ferromagnetic phase transition.



Systems showing such Curie-Weiss behavior in the magnetic susceptibility are typical ferromagnets such as Fe, Co, Ni, $\mathrm{CrO_2}$, $\mathrm{CoS_2}$ *etc.*

In materials that are ferromagnetic, magnetic domains, which are regions of aligned spins, tend to form below the Curie temperature T_C. The domains themselves need not be all aligned. The application of an external

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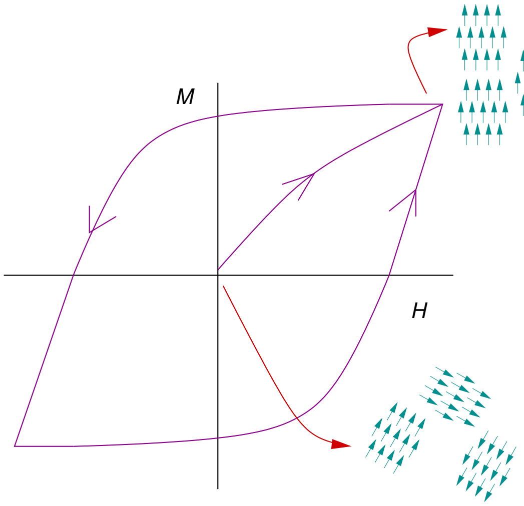
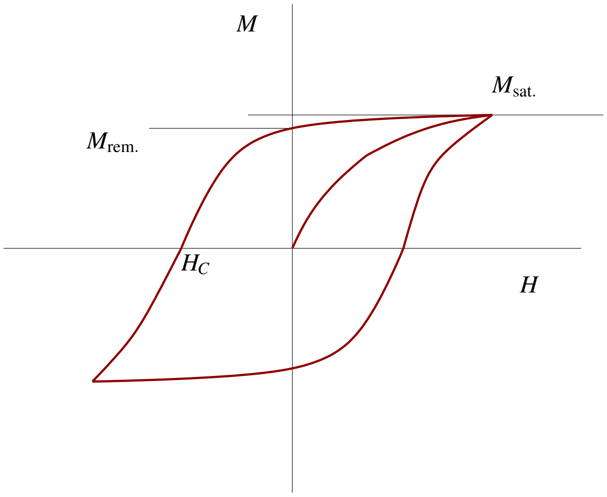
[1] In metallic solids, spins can communicate with one-another over long distances through the mediation of conduction electrons

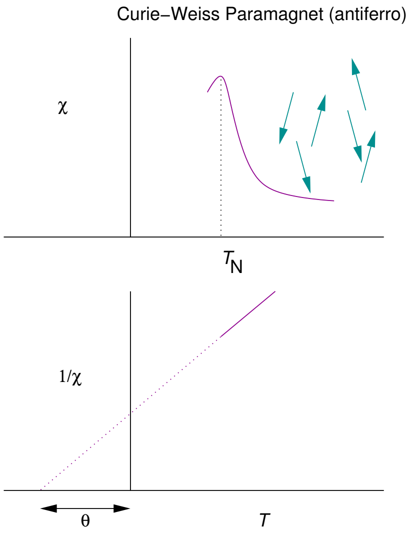
magnetic field however, tends to ensure that the net spin of each domain is aligned with the magnetic field. One of the indicators of the presence of magnetic domains is the characteristic hysteresis loop of ferromagnets.



The various regions of a hysteresis loop characterize the kind of ferromagnet that one has. The different parts of the loop are labelled in the next figure. The larger the coercive field H_c, the *harder* the magnet. A soft ferromagnet has no coercive field and hence no hysteresis.



In some systems, the internal field tends to antiallign spins. These systems are antiferromagnets. The Curie-Weiss plot is shifted so that θ is negative. In other words, even at 0 K, the spins cannot be lined up by applying a magnetic field. Only at some fictitious negative temperature will the spins all line up.

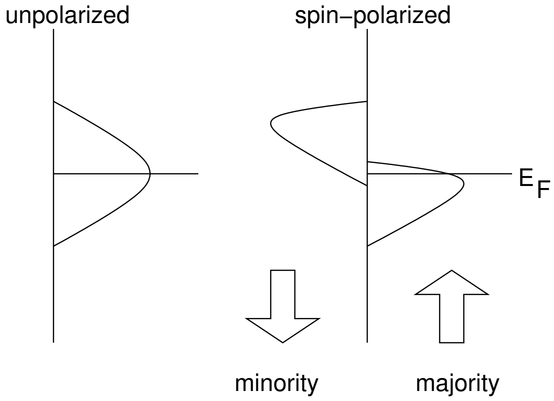


The intercept of the $1/\chi$ trace with the temperature axis is at some $\theta < 0$. In a well-behaved antiferromagnet, the phase transition from a paramagnet to an antiferromagnet takes place at the Néel temperature T_N and $T_N = -\theta$. Examples of antiferromagnets are Cr, Mn, Cr_2O_3, CoO, α-Fe_2O_3 ...

The origins of cooperative magnetism:

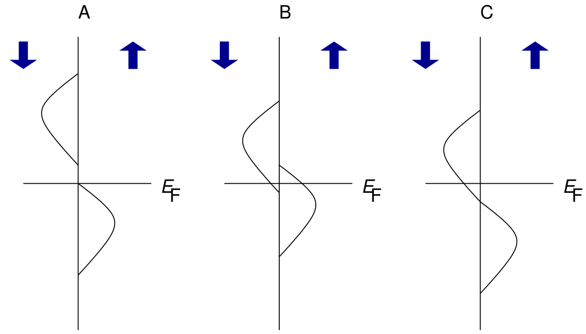
Valence d and f orbitals are more contracted than valence s and p orbitals. As a result, systems with d of f valence electrons are often magnetic.

In a magnetic d electron compound, spin-polarization splits the densities of state:



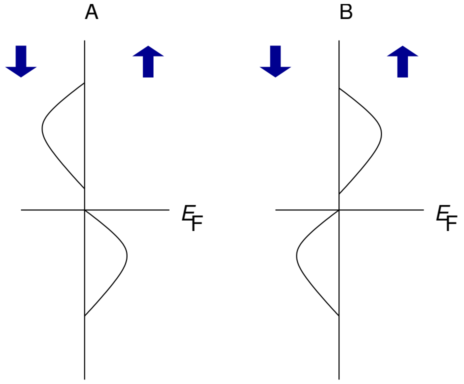
The states are usually called spin-up (↑) and spin down (↓), or alternately majority and minority. "Up" and "down" are not be thought of as actual directions in which the spins point.

In a ferromagnet, all the spins on the magnetic (d) ions point in the same direction. On the d ion site, the DOS might look like:



The figure shows the partial *d*-electron DOS of magnetic atoms in ferromagnets. **A** is a ferromagnetic insulator. These are quite rare. An example is the spinel $CdCr_2Se_4$. **B** is a typical ferromagnetic metal such as Fe. **C** is a ferromagnetic half-metal such as the pyrite compound CoS_2.

Antiferromagnetic compounds have two identical magnetic atoms **A** and **B** distinguished by the sense of the spin. The partial *d* DOS on one of the atoms cancels (in the sense of spin) the partial *d* DOS on the other atom. In the scheme below are the **A** and **B** site *d* partial DOS in an insulating antiferromagnet.



A ferrimagnet (example, the spinel $CoFe_2O_4$) is like an antiferromagnet, except the two sites **A** and **B** are both chemically and magnetically distinct. In the spinel $CoFe_2O_4$, **A** could represent the *d* DOS of the Co atoms and **A** could represent the *d* DOS of the Fe atoms.