

Classification of Magnetic Materials

All materials can be classified in terms of their magnetic behaviour falling into one of five categories depending on their bulk magnetic susceptibility. The two most common types of magnetism are diamagnetism and paramagnetism, which account for the magnetic properties of most of the periodic table of elements at room temperature (see figure 3).

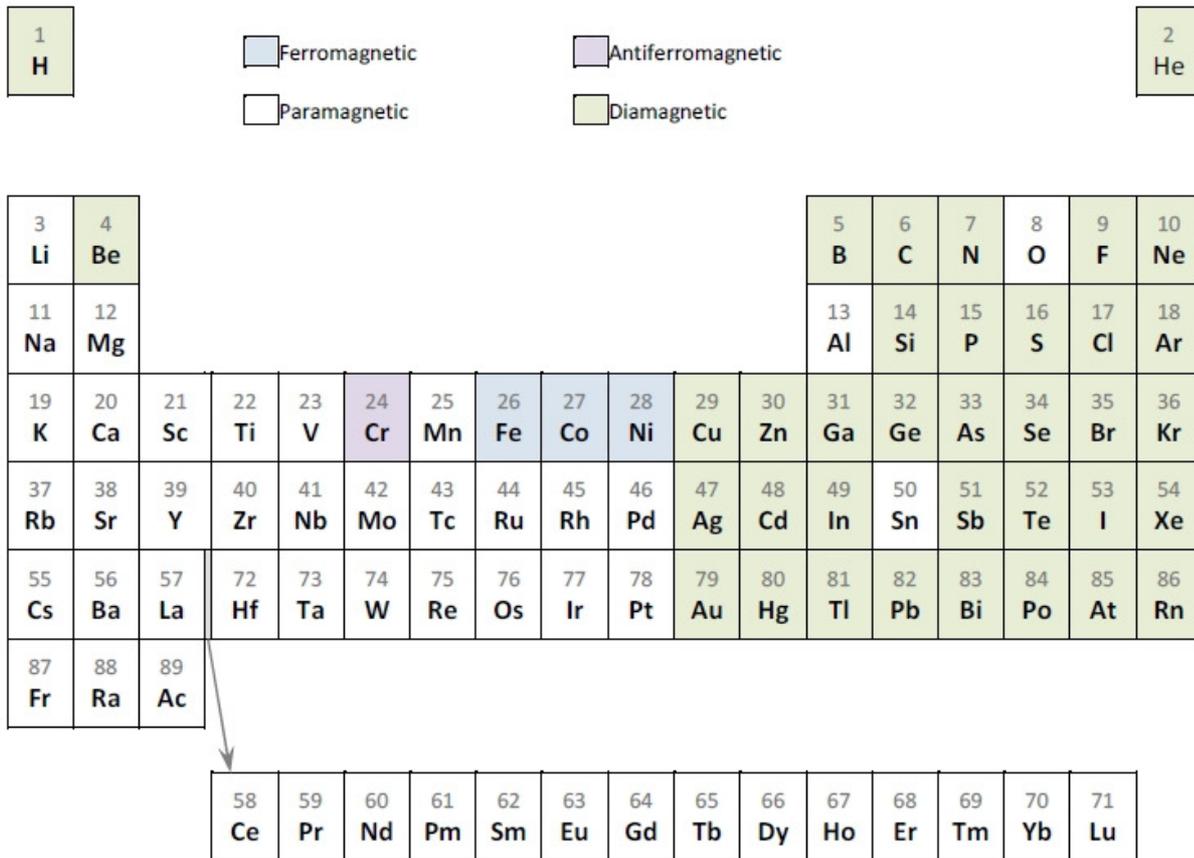


Figure 3: Periodic table

The two most common types of magnetism are diamagnetism and paramagnetism, which account for most of the periodic table of elements at room temperature. These elements are usually referred to as non-magnetic, whereas those which are referred to as magnetic are actually classified as ferromagnetic. The only other type of magnetism observed in pure elements at room temperature is antiferromagnetism. Finally, magnetic materials can also be classified as ferrimagnetic although this is not observed in any pure element but can only be found in compounds, such as the mixed oxides, known as ferrites, from which ferrimagnetism derives its name. The value of magnetic susceptibility falls into a particular range for each type of material and this is shown in table 2.

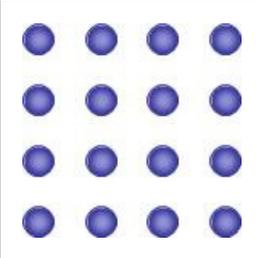
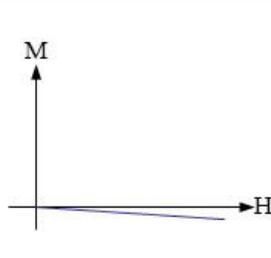
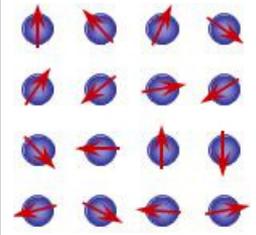
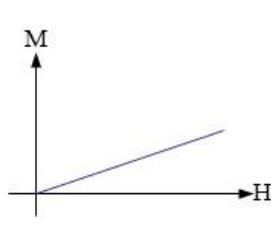
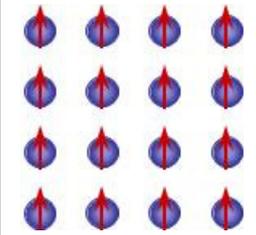
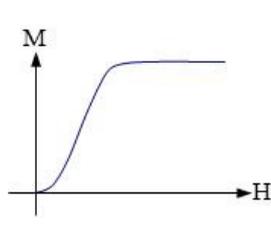
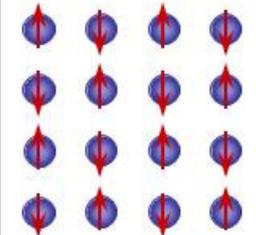
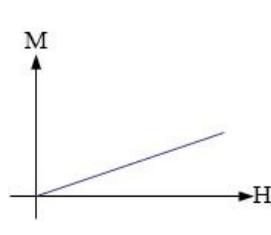
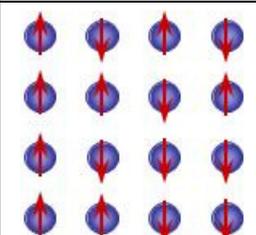
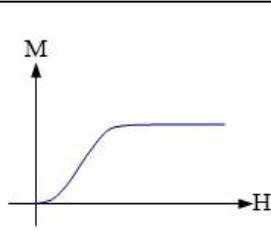
Type	Example	Atomic/Magnetic Behaviour		
Diamagnetism	Inert gases; many metals eg Au, Cu, Hg; non-metallic elements e.g. B, Si, P, S; many ions e.g. Na ⁺ , Cl ⁻ & their salts; diatomic molecules e.g. H ₂ , N ₂ ; H ₂ O; most organic compounds	Atoms have no magnetic moment. Susceptibility is small & negative, -10 ⁻⁶ to -10 ⁻⁵		
Paramagnetism	Some metals, e.g. Al; some diatomic gases, e.g. O ₂ , NO; ions of transition metals and rare earth metals, and their salts; rare earth oxides.	Atoms have randomly oriented magnetic moments. Susceptibility is small & positive, +10 ⁻⁵ to +10 ⁻³		
Ferromagnetism	Transition metals Fe, H, Co, Ni; rare earths with 64 ≤ Z ≤ 69; alloys of ferromagnetic elements; some alloys of Mn, e.g. MnBi, Cu ₂ MnAl.	Atoms have parallel aligned magnetic moments. Susceptibility is large (below T _c)		
Antiferromagnetism	Transition metals Mn, Cr & many of their compound, e.g. MnO, CoO, NiO, Cr ₂ O ₃ , MnS, MnSe, CuC ₁₂ .	Atoms have anti-parallel aligned magnetic moments. Susceptibility is small & positive, +10 ⁻⁵ to +10 ⁻³		
Ferrimagnetism	Fe ₃ O ₄ (magnetite); γ-Fe ₂ O ₃ (maghemite); mixed oxides of iron and other elements such as Sr ferrite.	Atoms have mixed parallel and anti-parallel aligned magnetic moments. Susceptibility is large (below T _c)		

Table 2: A summary of the different types of magnetic behaviour.

Diamagnetism

In a diamagnetic material the atoms have no net magnetic moment when there is no applied field. Under the influence of an applied field (H) the spinning electrons precess and this motion, which is a type of electric current, produces a magnetisation (M) in the opposite direction to that of the applied field. All materials have a diamagnetic effect, however, it is often the case that the diamagnetic effect is masked by the larger paramagnetic or ferromagnetic term. The value of susceptibility is independent of temperature.

Paramagnetism

There are several theories of paramagnetism, which are valid for specific types of material. The Langevin model, which is true for materials with non-interacting localised electrons, states that each atom has a magnetic moment which is randomly oriented as a result of thermal agitation. The application of a magnetic field creates a slight alignment of these moments and hence a low magnetisation in the same direction as the applied field. As the temperature increases, then the thermal agitation will increase and it will become harder to align the atomic magnetic moments and hence the susceptibility will decrease. This behaviour is known as the Curie law and is shown below in Equ.6, where C is a material constant called the Curie constant.

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

Equ.6

Materials which obey this law are materials in which the magnetic moments are localised at the atomic or ionic sites and where there is no interaction between neighbouring magnetic moments. The hydrated salts of the transition metals, e.g. $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, are examples of this type of behaviour as the transition metal ions, which have a magnetic moment, are surrounded by a number of non-magnetic ions / atoms, which prevent interaction between neighbouring magnetic moments.

In fact the Curie law is a special case of the more general Curie-Weiss law (equ.7), which incorporates a temperature constant (θ) and derives from Weiss theory, proposed for ferromagnetic materials, that incorporates the interaction between magnetic moments.

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

Equ.7

In this equation θ can either be positive, negative or zero. Clearly when $\theta = 0$ then the Curie-Weiss law equates to the Curie law. When θ is non-zero then there is an interaction between neighbouring magnetic moments and the material is only paramagnetic above a certain transition temperature. If θ is positive then the material is ferromagnetic below the transition temperature and the value of θ corresponds to the transition temperature (Curie temperature, T_C). If θ is negative then the material is antiferromagnetic below the transition temperature (Néel temperature, T_N), however the value of θ does not relate to T_N . It is important to note that this equation is only valid when the material is in a paramagnetic state. It is also not valid for many metals as the electrons contributing to the magnetic moment are not localised. However, the law does apply to some metals, e.g. the rare-earths, where the 4f electrons, that create the magnetic moment, are closely bound.

The Pauli model of paramagnetism is true for materials where the electrons are free and interact to form a conduction band this is valid for most paramagnetic metals. In this model the conduction electrons are considered essentially to be free and under an applied field an imbalance between electrons with opposite spin is set up leading to a low magnetisation in the same direction as the applied field. The susceptibility is independent of temperature, although the electronic band structure may be affected, which will then have an effect on the susceptibility.

Ferromagnetism

Ferromagnetism is only possible when atoms are arranged in a lattice and the atomic magnetic moments can interact to align parallel to each other. This effect is explained in classical theory by the presence of a molecular field within the ferromagnetic material, which was first postulated by Weiss in 1907. This field is sufficient to magnetise the material to saturation. In quantum mechanics, the Heisenberg model of ferromagnetism describes the parallel alignment of magnetic moments in terms of an exchange interaction between neighbouring moments.

Weiss postulated the presence of magnetic domains within the material, which are regions where the atomic magnetic moments are aligned. The movement of these domains determines how the material responds to a magnetic field and as a consequence the susceptibility is a function of applied magnetic field. Therefore, ferromagnetic materials are usually compared in terms of saturation magnetisation (magnetisation when all domains are aligned) rather than susceptibility.

In the periodic table of elements only Fe, Co and Ni are ferromagnetic at and above room temperature. As ferromagnetic materials are heated then the thermal agitation of the atoms means that the degree of alignment of the atomic magnetic moments decreases and hence the saturation magnetisation also decreases. Eventually the thermal agitation becomes so great that the material becomes paramagnetic; the temperature of this transition is the Curie temperature, T_C (Fe: $T_C=770^\circ\text{C}$, Co: $T_C=1131^\circ\text{C}$ and Ni: $T_C=358^\circ\text{C}$). Above T_C then the susceptibility varies according to the Curie-Weiss law.

Antiferromagnetism

In the periodic table the only element exhibiting antiferromagnetism at room temperature is chromium. Antiferromagnetic materials are very similar to ferromagnetic materials but the exchange interaction between neighbouring atoms leads to the anti-parallel alignment of the atomic magnetic moments. Therefore, the magnetic field cancels out and the material appears to behave in the same way as a paramagnetic material. Like ferromagnetic materials these materials become paramagnetic above a transition temperature, known as the Néel temperature, T_N . (Cr: $T_N=37^\circ\text{C}$).

Ferrimagnetism

Ferrimagnetism is only observed in compounds, which have more complex crystal structures than pure elements. Within these materials the exchange interactions lead to parallel alignment of atoms in some of the crystal sites and anti-parallel alignment of others. The material breaks down into magnetic domains, just like a ferromagnetic material and the magnetic behaviour is also very similar, although ferrimagnetic materials usually have lower saturation magnetisations. For example in Barium ferrite ($\text{BaO}\cdot 6\text{Fe}_2\text{O}_3$) the unit cell contains 64 ions of which the barium and oxygen ions have no magnetic moment, 16 Fe^{3+} ions have moments aligned parallel and 8 Fe^{3+} aligned anti-parallel giving a net magnetisation parallel to the applied field, but with a relatively low magnitude as only $\frac{1}{8}$ of the ions contribute to the magnetisation of the material.