

7. Ferromagnetism

In this section we will discuss some materials in which the net effect of the magnetic dipole moments in the material is much greater than in the case of paramagnetism or diamagnetism. The phenomenon is called ferromagnetism. Recall that

$$\vec{B} = \mu_0 (\vec{H} + \vec{M}) \quad (1)$$

In paramagnetic and diamagnetic materials the induced magnetic moments are usually so weak that we don't have to worry about the additional fields produced by the magnetic moments. In other words, the magnetic susceptibilities are usually so low ($\sim 10^{-5}$) in paramagnetism and diamagnetism that the term

$$\vec{M} = \chi_m \vec{H} \quad (2)$$

can be ignored in (1), so that

$$\vec{B} \approx \mu_0 \vec{H}, \quad (3)$$

i.e., \vec{B} in paramagnetic or diamagnetic materials is almost the same as in free space. In fact we have actually used this approximation to find both paramagnetic and diamagnetic susceptibilities. For ferromagnetic materials, however, the magnetic moments induced by applied magnetic fields are quite enormous and have a great effect on the fields themselves. In fact, the induced moments are so strong that they are often the dominant effect in producing the observed fields. In other words, when a ferromagnetic material is magnetized, we will often have $|\vec{M}| \gg |\vec{H}|$, so that

$$\vec{B} \approx \mu_0 \vec{M}$$

(4) → See Figure 19-1, p. 465
Debye & Fig. 6.29
p. 281
Griffiths
3rd Ed.

The question is, why are the magnetic moments so strong - how does it all work? A detailed explanation can only be provided by quantum mechanics.

However we will take a classical approach suggested by Weiss who put forward the following hypotheses in 1907 (i.e., well before quantum mechanics was developed):

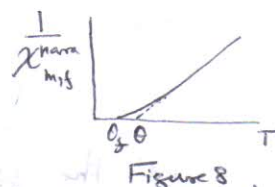
(i) A ferromagnetic specimen of macroscopic dimensions contains, in general, a

number of small regions (domains) which are spontaneously magnetized; the magnitude of the spontaneous magnetization of the specimen is determined by the vector sum of the magnetic moments of the individual domains.

- (ii) Within each domain the spontaneous magnetization is due to the existence of a "molecular field" which tends to produce a parallel alignment of the atomic dipoles.

Of the elements, only Fe, Ni, Co, Gd, and Dy are ferromagnetic, although there are a relatively large number of ferromagnetic alloys and oxides. Above a critical temperature θ_f , known as the ferromagnetic Curie temperature, the spontaneous magnetization vanishes and the material becomes paramagnetic. Well above θ_f the ^{paramagnetic} susceptibility follows the Curie-Weiss law,

$$\chi_{m,s}^{\text{para}} = \frac{C}{T - \theta} \quad (5)$$



where C is the Curie constant; the temperature θ is called the paramagnetic Curie temperature and is usually some degrees higher than θ_f . According to the

	Fe	Co	Ni	Curie-Weiss law, a plot of $\frac{1}{\chi}$ vs T should yield a straight line, the intercept along the T -axis being equal to θ . Experiments show that this law is indeed satisfied with considerable accuracy except in the region close to the Curie point.
$\theta_f (K)$	1043	1393	631	
$\theta (K)$	1093	1428	650	

Figure 8 shows a schematic representation of the behavior of the ferromagnetic metals above the Curie point; the slight curvature leads to the distinction between the ferromagnetic and paramagnetic Curie points.

Students, it is important for you to understand that the spontaneous magnetization (below θ_f) refers to a single domain - one of many within a ferromagnetic material below its θ_f . Within each domain the spontaneous magnetization has a specific direction but this direction may vary randomly from one domain to the other. For a ferromagnetic specimen that has never been subjected to an external magnetic field; below its θ_f the sum of the vectors representing the resultant magnetic dipole moments of the individual domains may therefore vanish. Thus in spite of having spontaneously magnetized domains at room temperature, an 'ordinary'

piece of iron is not necessarily magnetized as a whole.

The Curie-Weiss Law

Spontaneous magnetization implies cooperation between the atomic dipoles within a single domain, i.e., there must be some kind of interaction between the atoms which produces the tendency for parallel alignment of the atomic magnetic dipoles. In order to obtain a phenomenological description of spontaneous magnetization, Weiss assumed that the molecular field H_m acting on a given dipole may be written in the form

$$H_m = H + H_{int} \quad (6)$$

where H is the applied field and H_{int} is the internal field which is proportional to the magnetization, that is,

$$H_{int} = \lambda M, \quad (7)$$

so that

$$H_m = H + \lambda M, \quad (8)$$

where M is the magnetization and λ is the Weiss constant. It is this internal field which provides the cooperative effect that leads to spontaneous magnetization for $T < \theta_f$ in a ferromagnetic material. The orienting effect (or cooperative effect) of this internal field is opposed by thermal agitation, and for $T > \theta_f$ the ordered orientation of the atomic dipoles in the same direction is destroyed. The material becomes paramagnetic. We will now show that a molecular field of the type given in Eq.(8) indeed leads to the Curie-Weiss law.

The paramagnetic susceptibility as given by Curie's law is,

$$\chi_m^{para} = \frac{M}{H} = \frac{C}{T} \quad (9)$$

where M - magnetization of the paramagnetic specimen, T - its temperature, C - Curie constant for the specimen, H - applied field.

So,

$$M = \frac{C}{T} H \quad (10)$$

for a paramagnetic material. Now consider the paramagnetic phase of a ferromagnetic material (i.e., temperature greater than θ): an applied field H will cause a finite magnetization M and this in turn will cause a finite internal field $H_{int} (= \lambda M)$.

If $\chi_{m,f}^{para}$ is the paramagnetic susceptibility of the ferromagnetic specimen, then

$$\chi_{m,f}^{para} = \frac{M}{H} \quad (11)$$

where,

$$M = \frac{c}{T} (H + H_{int}) = \frac{c}{T} (H + \lambda M) \quad (12)$$

$$\Rightarrow MT - c\lambda M = cH \Rightarrow M(T - c\lambda) = cH$$

$$\therefore M = \frac{c}{T - c\lambda} H \quad (13)$$

$$\chi_{m,f}^{para} = \frac{M}{H} = \frac{c}{T - c\lambda} = \frac{c}{T - \theta} \quad (5)$$

where,

$$\theta = c\lambda \quad (15)$$

Not in syllabus but relevant information

- It can be shown through simple physical arguments that $\lambda \sim 10^4$. This large value plays a crucial role in spontaneous magnetization. See Dekker p. 472.
- For $T < \theta_f$, the spontaneous magnetization itself is a function of temperature. - Dekker p. 469
- Experiments have shown that the magnetization is essentially associated with electron spins rather than with their orbital motions. - Dekker Section 19-3 p. 468.

6.4.2 Ferromagnetism

In a linear medium the alignment of atomic dipoles is maintained by a magnetic field imposed from the outside. Ferromagnets—which are emphatically *not* linear⁷—require no external fields to sustain the magnetization; the alignment is “frozen in.” Like paramagnetism, ferromagnetism involves the magnetic dipoles associated with the spins of unpaired electrons. The new feature, which makes ferromagnetism so different from paramagnetism, is the interaction between nearby dipoles: In a ferromagnet, *each dipole “likes” to point in the same direction as its neighbors*. The reason for this preference is essentially quantum mechanical, and I shall not endeavor to explain it here; it is enough to know that the correlation is so strong as to align virtually 100% of the unpaired electron spins. If you could somehow magnify a piece of iron and “see” the individual dipoles as tiny arrows, it would look something like Fig. 6.25, with all the spins pointing the same way.

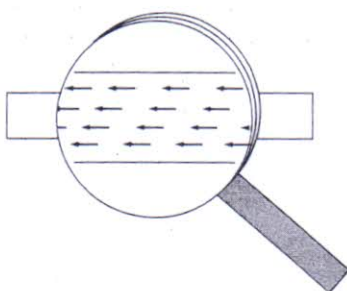
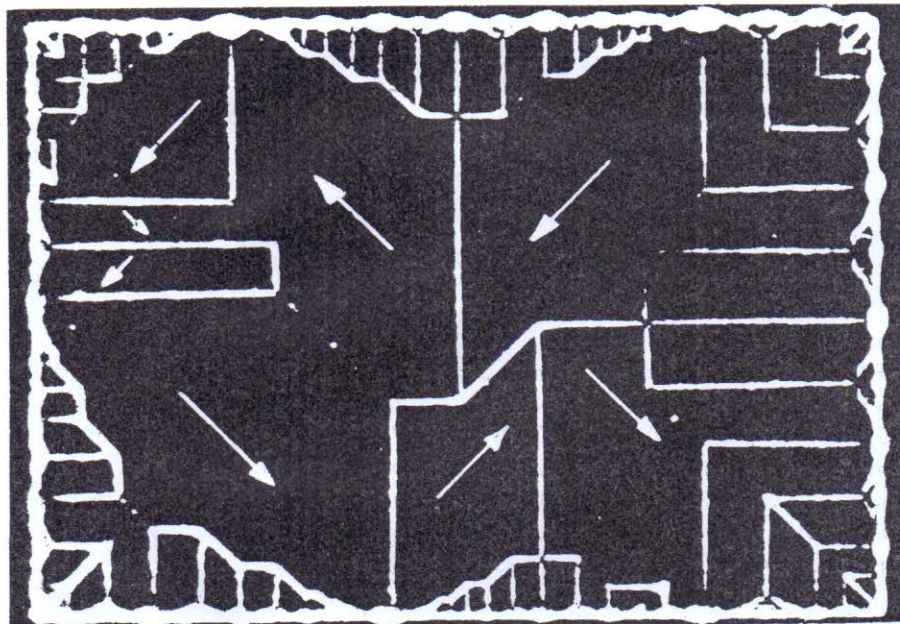


Figure 6.25

But if that is true, why isn't every wrench and nail a powerful magnet? The answer is that the alignment occurs in relatively small patches, called **domains**. Each domain contains billions of dipoles, all lined up (these domains are actually *visible* under a microscope, using suitable etching techniques—see Fig. 6.26), but the domains *themselves* are randomly oriented. The household wrench contains an enormous number of domains, and their magnetic fields cancel, so the wrench as a whole is not magnetized. (Actually, the orientation of domains is not *completely* random; within a given crystal there may be some preferential alignment along the crystal axes. But there will be just as many domains pointing one way as the other, so there is still no large-scale magnetization. Moreover, the crystals themselves are randomly oriented within any sizable chunk of metal.)

How, then, would you produce a **permanent magnet**, such as they sell in toy stores? If you put a piece of iron into a strong magnetic field, the torque $\mathbf{N} = \mathbf{m} \times \mathbf{B}$ tends to align the dipoles parallel to the field. Since they like to stay parallel to their neighbors, most of the dipoles will resist this torque. However, at the *boundary* between two domains, there

⁷In this sense it is misleading to speak of the susceptibility or permeability of a ferromagnet. The terms *are* used for such materials, but they refer to the proportionality factor between a *differential* increase in \mathbf{H} and the resulting *differential* change in \mathbf{M} (or \mathbf{B}); moreover, they are not *constants*, but functions of \mathbf{H} .



Ferromagnetic domains. (Photo courtesy of R. W. DeBlois)

Figure 6.26

are *competing* neighbors, and the torque will throw its weight on the side of the domain most nearly parallel to the field; this domain will win over some converts, at the expense of the less favorably oriented one. The net effect of the magnetic field, then, is to *move the domain boundaries*. Domains parallel to the field grow, and the others shrink. If the field is strong enough, one domain takes over entirely, and the iron is said to be “saturated.”

It turns out that this process (the shifting of domain boundaries in response to an external field) is not entirely reversible: When the field is switched off, there will be *some* return to randomly oriented domains, but it is far from complete—there remains a preponderance of domains in the original direction. The object is now a permanent magnet.

A simple way to accomplish this, in practice, is to wrap a coil of wire around the object to be magnetized (Fig. 6.27). Run a current I through the coil; this provides the external magnetic field (pointing to the left in the diagram). As you increase the current, the field increases, the domain boundaries move, and the magnetization grows. Eventually, you reach the saturation point, with all the dipoles aligned, and a further increase in current has no effect on M (Fig. 6.28, point b).

Now suppose you *reduce* the current. Instead of retracing the path back to $M = 0$, there is only a *partial* return to randomly oriented domains. M decreases, but even with the current off there is some residual magnetization (point c). The wrench is now a permanent

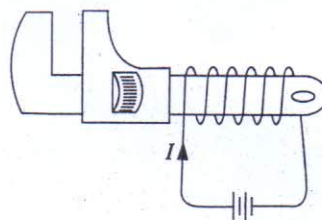


Figure 6.27

magnet. If you want to eliminate the remaining magnetization, you'll have to run a current backwards through the coil (a negative I). Now the external field points to the right, and as you increase I (negatively), M drops down to zero (point d). If you turn I still higher, you soon reach saturation in the other direction—all the dipoles now pointing to the *right* (e). At this stage switching off the current will leave the wrench with a permanent magnetization to the right (point f). To complete the story, turn I on again in the positive sense: M returns to zero (point g), and eventually to the forward saturation point (b).

The path we have traced out is called a **hysteresis loop**. Notice that the magnetization of the wrench depends not only on the applied field (that is, on I), but also on its previous magnetic “history.”⁸ For instance, at three different times in our experiment the current was zero (a , c , and f), yet the magnetization was different for each of them. Actually, it is customary to draw hysteresis loops as plots of B against H , rather than M against I . (If our coil is approximated by a long solenoid, with n turns per unit length, then $H = nI$, so H and I are proportional. Meanwhile, $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, but in practice M is huge compared to H , so to all intents and purposes \mathbf{B} is proportional to \mathbf{M} .)

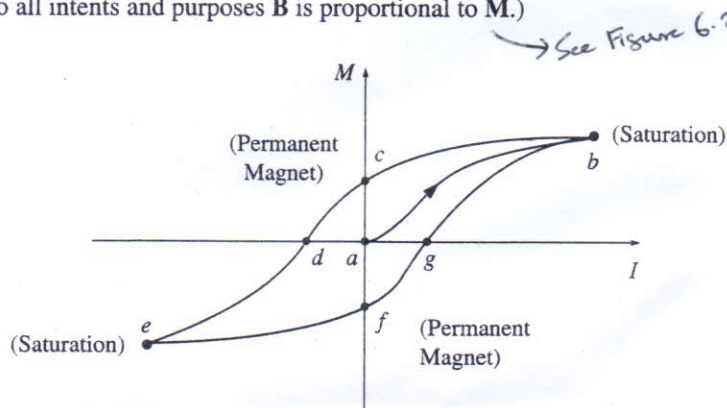


Figure 6.28

⁸Etymologically, the word *hysteresis* has nothing to do with the word *history*—nor with the word *hysteria*. It derives from a Greek verb meaning “to lag behind.”

To make the units consistent (teslas), I have plotted $(\mu_0 H)$ horizontally (Fig. 6.29); notice, however, that the vertical scale is 10^4 times greater than the horizontal one. Roughly speaking, $\mu_0 \mathbf{H}$ is the field our coil *would* have produced in the absence of any iron; \mathbf{B} is what we *actually* got, and compared to $\mu_0 \mathbf{H}$ it is gigantic. A little current goes a long way when you have ferromagnetic materials around. That's why anyone who wants to make a powerful electromagnet will wrap the coil around an iron core. It doesn't take much of an external field to move the domain boundaries, and as soon as you've done that, you have all the dipoles in the iron working with you.

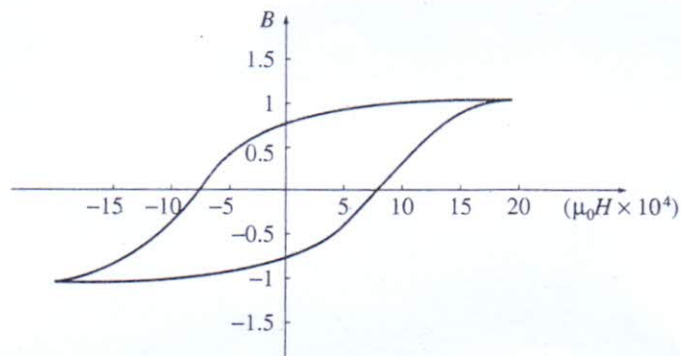


Figure 6.29

One final point concerning ferromagnetism: It all follows, remember, from the fact that the dipoles within a given domain line up parallel to one another. Random thermal motions compete with this ordering, but as long as the temperature doesn't get too high, they cannot budge the dipoles out of line. It's not surprising, though, that *very* high temperatures do destroy the alignment. What *is* surprising is that this occurs at a precise temperature (770°C , for iron). Below this temperature (called the **Curie point**), iron is ferromagnetic; above, it is paramagnetic. The Curie point is rather like the boiling point or the freezing point in that there is no *gradual* transition from ferro- to para-magnetic behavior, any more than there is between water and ice. These abrupt changes in the properties of a substance, occurring at sharply defined temperatures, are known in statistical mechanics as **phase transitions**.

Problem 6.20 How would you go about *demagnetizing* a permanent magnet (such as the wrench we have been discussing, at point *c* in the hysteresis loop)? That is, how could you restore it to its original state, with $M = 0$ at $I = 0$?

Problem 6.21

(a) Show that the energy of a magnetic dipole in a magnetic field \mathbf{B} is given by

$$U = -\mathbf{m} \cdot \mathbf{B}. \quad (6.34)$$

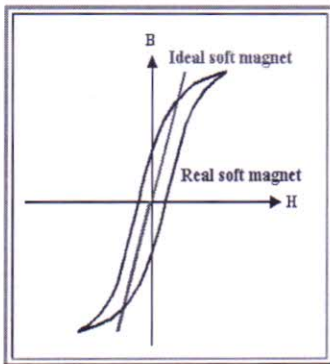
Definitions

Lets quickly go over the three questions from the preceding sub-chapter

- 1. What kind of hystereses curve do I need for the application I have in mind?

Lets look at two "paradigmatic" applications: A **transformer core** and a **magnetic memory**.

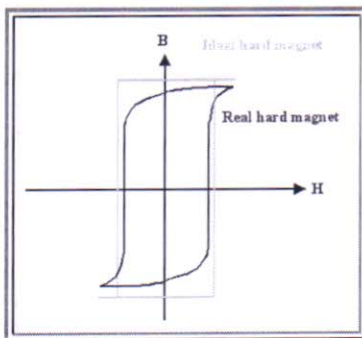
- The transformer core is ferromagnetic in order to "transport" a large magnetic flux B produced by the primary coil to the secondary coil. What I want is that the induced flux B follows the primary field H as closely as possible.
- In other words: There should be *no* hystereses loop - just a straight line, as shown below



- The ideal curve, without any hystereses, does not exist. What you get is something like the curve shown for a real **soft magnet** - because that is what we call a material with a kind of slender hystereses curve and thus small values of coercivity and remanence
- If we switch on a positive field H and then go back to zero again, a little bit of magnetization is left. For a rather small reverse field, the magnetic flux reverses, too - the flux B follows H rather closely, if not exactly.
- Hystereses losses are small, because the area enclosed in the hystereses loop is small.
- But *some* losses remain, and the "transformer core" industry will be very happy if you can come up with a material that is just 1 % or 2 % "softer" than what they have now.
- Beside losses, you have another problem: If you vary H sinusoidally, the output will be a somewhat distorted sinus, because B does not follow H linearly. This may be a problem when transforming *signals*.

A soft magnetic material will obviously not make a good **permanent magnet**, because its remaining magnetization (its remanence) after switching off the magnetic field H is small.

- But a permanent magnet is what we want for a **magnetic storage material**. Here we want to induce a large permanent magnetization by some external field (produced by the "writing head" of our storage device) that stays intact for many years if needs be. Some more information about magnetic storage can be found in an extra module
- It should be *strong enough* - even so it is contained in a tiny area of the magnetic material on the tape or the storage disc - to produce a measurable effect if the reading head moves over it. It should not be *too strong*, however, because that would make it too difficult to erase it if we want to overwrite it with something else. In short, it should look like this



- We can define what we want in terms of coercivity and remance. Ideally, the hystereses curve is very "square".
- At some minimum field, the magnetization is rather large and does not change much anymore.
- If we reverse the field direction, not much happens for a while, but as soon as we move above slightly above the coercivity value, the magnetization switches direction completely.
- Ferromagnetic losses are unavoidable, we simply must live with them

Pretty much all possible applications - consult the list in the next section - either calls for *soft* or for *hard* magnets; there isn't much in between.

- So we now must turn to the second and third question:

Tailoring Hystereses Curves

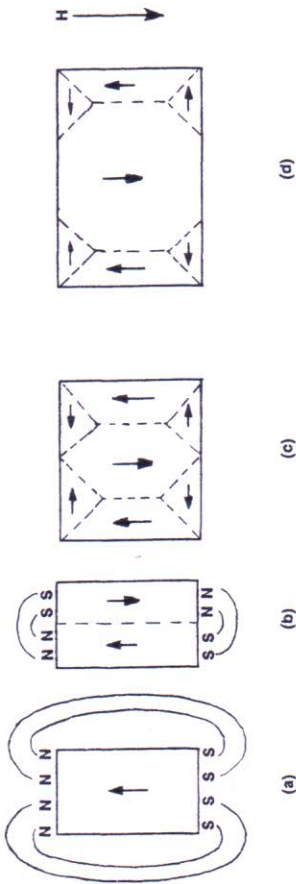


Figure 15.9. (a) Spontaneous alignment of all spins in a single direction. (b) Division into two magnetic domains having opposite spin directions. (c) Closure domains in a cubic crystal. (d) Growth of a domain whose spins are parallel to an external magnetic field. (The domain walls are *not* identical with the grain boundaries.)

parallel to each other. It is this interplay between exchange energy, which demands parallel spin alignment, and magnetostatic energy, which supports antiparallel spins, that leads eventually to an energetically most favorable domain size (which is about $1-100\ \mu\text{m}$).

A further reduction in magnetostatic energy can be obtained if the magnetic flux follows a completely closed path within a crystal so that no exterior poles are formed. Indeed, “closure” domain structures, as shown in Fig. 15.9(c), are observed in cubic crystals.

Another question which needs to be answered pertains to whether the flip from one spin direction into the other occurs in one step, i.e., between two adjacent atoms, or instead over an extended range of atoms. Again, the above-mentioned exchange energy, which supports a parallel spin alignment, hinders a spontaneous flip-over. Instead, a gradual rotation over several hundred atomic distances is energetically more favorable. The region between individual domains in which the spins rotate from one direction into the next is called a domain wall or a **Bloch wall**.

Finally, we may ask the question whether and how those domain walls can be made visible. The most common method, devised by Bitter in 1931, utilizes an aqueous suspension of very finely dispersed Fe_3O_4 particles which is applied to the polished surface of a test material. These particles are attracted to the domain wall endings and can then be observed as fine lines under an optical microscope. Another method exploits the rotation of the plane of polarization of reflected light from differently magnetized areas (**Kerr effect**).

We mentioned above that an external magnetic field causes a movement of the domain walls. The movement is, as a rule, not continuous, but occurs most of the time in distinct jumps. This is known as the **Barkhausen effect**, which utilizes an induction coil wound around a ferromagnetic rod. The former is connected to an amplifier and a loudspeaker. Audible clicks are

heard when a permanent magnet approaches the iron rod. The wall motions may be impeded by imperfections in the crystal, such as by particles of a second phase, oxides, holes, or cracks. A second type of impediment to free domain wall motion stems from dislocations, i.e., from residual stresses in the crystal caused by grinding, polishing, or plastic deformation.

Cold work enlarges the coercivity and the area within the hysteresis loop. Further, cold work decreases the permeability and causes a clockwise rotation of the hysteresis curve. In short, mechanical hardness and magnetic hardness parallel each other in many cases. (There exist exceptions, however, such as in the case of silicon additions to iron, which makes the material magnetically softer and mechanically harder, see Section 17.2.3.) Recrystallization and grain growth by annealing at suitable temperatures relieve the stresses and restore the soft-magnetic properties.

We shall return to ferromagnetism in Section 15.4 and Chapter 16.

15.1.4. Antiferromagnetism

Antiferromagnetic materials exhibit, just as ferromagnetics, a spontaneous alignment of moments below a critical temperature. However, the responsible neighboring atoms in antiferromagnetics are aligned in an antiparallel fashion (Fig. 15.10). Actually, one may consider an antiferromagnetic crystal to be divided into two interpenetrating sublattices, A and B, each of which has a spontaneous parallel alignment of spins. Figure 15.10 depicts the spin alignments for two manganese compounds. (Only the spins of the manganese ions contribute to the antiferromagnetic behavior.) Figure 15.10(a) im-

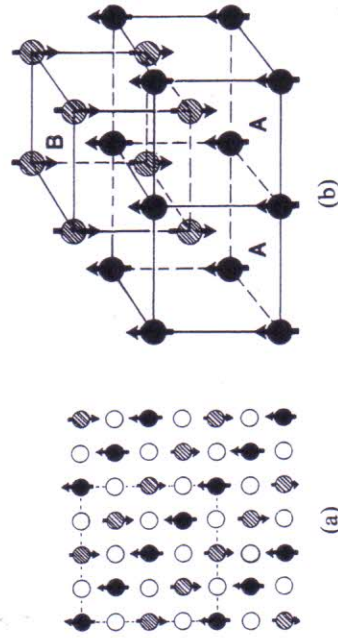


Figure 15.10. Schematic representation of spin alignments for antiferromagnetics at 0 K. (a) Display of a (100) plane of MnO. The gray (spin down) and black (spin up) circles represent the Mn ions. The oxygen ions (open circles) do not contribute to the antiferromagnetic behavior. MnO has a NaCl structure. (b) Three-dimensional representation of the spin alignment of manganese ions in MnF_2 . (The fluorine ions are not shown.) This figure demonstrates the interpenetration of two manganese sublattices, A and B, having antiparallel aligned moments.

Ferrimagnetic materials are of great technical importance. They exhibit a spontaneous magnetic moment (Fig. 15.9) and hysteresis (Fig. 15.6) below a Curie temperature, just as iron, cobalt, or nickel. In other words, ferrimagnetic materials possess, similarly as ferromagnetics, small domains in which the electron spins are spontaneously aligned in parallel. The main difference from ferromagnetics is, however, that ferrimagnetics are ceramic materials (oxides) and that they are poor electrical conductors. A large resistivity is often desired for high-frequency applications (e.g., to prevent eddy currents in cores of coils, see Chapter 17).

To explain the spontaneous magnetization in ferrimagnetics, Néel proposed that two sublattices should exist in these materials (just as in antiferromagnetics) each of which contains ions whose spins are aligned parallel to each other. The crucial point is that each of the sublattices contain *different* numbers of magnetic ions. This causes some of the magnetic moments to remain uncanceled. As a consequence, a net magnetic moment results. Ferrimagnetic materials can thus be described as *imperfect antiferromagnetics*. The crystallography of ferrites is rather complex. We defer its discussion until later. For the time being, it suffices to know that there are two types of lattice sites which are available to be occupied by the metal ions. They are called A sites and B sites. (As before, oxygen ions do not contribute to the magnetic moments.)

We will now discuss as an example nickel ferrite, $\text{NiO} \cdot \text{Fe}_2\text{O}_3$. The Fe^{3+} ions are equally distributed between A and B sites (Fig. 15.12), and since ions on A and B sites exhibit spontaneous magnetization in opposite directions, we expect overall cancellation of spins for these ions. Specifically, atomic iron possesses six 3d-electrons and two 4s-electrons ($3d^6 4s^2$, see Appendix 3). The Fe^{3+} ions are deprived of three electrons, so that five d-electrons, or five spin moments per atom, remain in its outermost shell. This is indicated in Fig. 15.12.

A sites	B sites
8 Fe^{3+}	8 Fe^{3+} 8 Ni^{2+}
↑↑↑↑↑	↓↓↓↓↓ ↓↓

Figure 15.12. Distribution of spins upon A and B sites for the inverse spinel $\text{NiO} \cdot \text{Fe}_2\text{O}_3$. The spins within one site are arranged considering Hund's rule (Fig. 15.4). The iron ions are equally distributed among the A and B sites. The nickel ions are only situated on B sites. The relevance of the number of ions per unit cell is explained later on in the text.

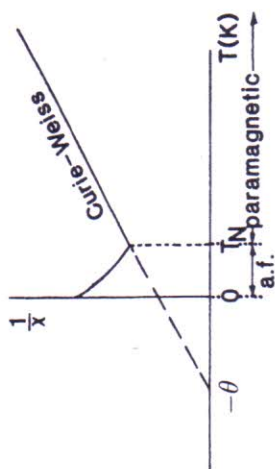


Figure 15.11. Schematic representation of the temperature dependence of a polycrystalline antiferromagnetic (a.f.) material.

plies that the ions in a given {110} plane possess parallel spin alignment, whereas ions in the adjacent plane have antiparallel spins with respect to the first plane. Thus, the magnetic moments of the solid cancel each other and the material as a whole has no net magnetic moment.

Antiferromagnetic materials are paramagnetic above the **Néel temperature** T_N , i.e., they obey there a linear $T = f(1/\chi)$ law (see Fig. 15.11). Below T_N , however, the inverse susceptibility may rise with decreasing temperature. The extrapolation of the paramagnetic line to $1/\chi = 0$ yields a negative θ . Thus, the Curie-Weiss law (15.2) needs to be modified for antiferromagnetics to read

$$\chi = \frac{C}{T - (-\theta)} = \frac{C}{T + \theta} \quad (15.4)$$

The Néel temperature is often below room temperature (Table 15.2). Most antiferromagnetics are found among ionic compounds. They are insulators or semiconductors. Essentially no practical application for antiferromagnetism is known at this time. (See, however, the use of "canted" antiferromagnetics, described in Section 17.5, which are materials in which the magnetic moments of the two sublattices are not completely antiparallel. This results in a small net magnetization.)

Table 15.2. Characteristic Data for Some Antiferromagnetic Materials.

Substance	T_N (K)	$-\theta$ (K)
MnO	116	610
MnF ₂	67	82
α -Mn	100	?
FeO	198	570
NiO	523	~2000
CoO	293	330
Cr	310	?

Table 15.3. Calculated and Measured Number of Bohr Magneton for Some Ferrites.

Ferrite	Mn	Fe	Co	Ni	Cu
Calculated μ_B	5	4	3	2	1
Measured μ_B	4.6	4.1	3.7	2.3	1.3

The electron configuration of nickel in its atomic state is $3d^8 4s^2$. Two electrons are stripped in the Ni^{2+} ion so that eight d -electrons per atom remain. They are arranged, according to Hund's rule (Fig. 15.4), to yield two net magnetic moments (Fig. 15.12). All nickel ions are accommodated on the B sites. Nickel ferrite is thus expected to have two uncanceled spins, i.e., two Bohr magnetons (per formula unit), which is essentially observed (see Table 15.3).

The small discrepancy between experiment and calculation is believed to be caused by some contributions of orbital effects to the overall magnetic moment, and by a slight deviation of the distribution of metal ions on the A and B sites from that shown in Fig. 15.12.

The unit cell of cubic ferrites contains a total of 56 ions. Some of the metal ions are situated inside a *tetrahedron* formed by the oxygen ions. These are the above-mentioned A sites (Fig. 15.13(a)). Other metal ions are arranged in the center of an *octahedron* and are said to be on the B sites (Fig. 15.13(b)). The A and B sites are nestled inside a unit cell (Fig. 15.13(c)).

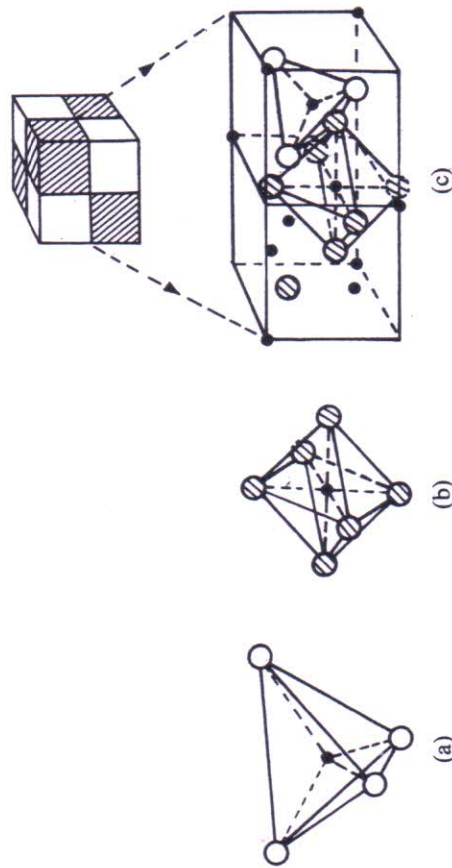


Figure 15.13. Crystal structure of cubic ferrites. The small filled circles represent metal ions, the large open or shaded circles represent oxygen ions: (a) tetrahedral or A sites; (b) octahedral or B sites; and (c) one-fourth of the unit cell of a cubic ferrite. Adapted from J. Smit, and H.P.J. Wijn, *Ferrites*, Wiley, New York (1959).

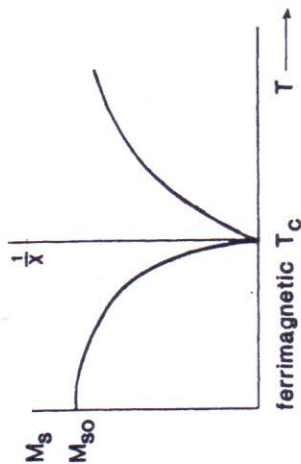


Figure 15.14. Schematic representation of the temperature dependence of the saturation magnetization, M_s , and the reciprocal susceptibility for ferrites.

Now, only 8 tetrahedral sites and 16 octahedral sites are occupied by metal ions. In $NiO \cdot Fe_2O_3$ twice as many iron ions as nickel ions are present. Eight of the Fe^{3+} ions per unit cell occupy the A sites, eight of them occupy some of the B sites and the eight Ni^{2+} ions fill the remaining B sites (Fig. 15.12). This distribution is called an *inverse spinel structure* (in contrast to a *normal spinel*, such as for $ZnO \cdot Fe_2O_3$, in which all Fe^{3+} ions occupy the B sites).

The temperature dependence of most ferrimagnetics is very similar to ferromagnetics (Fig. 15.14): The saturation magnetization decreases with increasing temperature until it vanishes at a Curie temperature, T_C . Above T_C , ferrimagnetics behave paramagnetically, having a nonlinear $1/\chi$ versus T relationship.

In conclusion, this section described, in a mostly qualitative way, the difference between dia-, para-, ferro-, antiferro-, and ferrimagnetism. In the sections to come, we shall again pick up the different forms of magnetism and deepen our understanding of these phenomena by following essentially the train of thought brought forward by Langevin, Weiss, and Néel.

15.2. Langevin Theory of Diamagnetism

We shall now develop the classical theory of diamagnetism in a quantitative way as put forward by Langevin at the turn of the 20th century.

We stated before that the orbital motion of an electron about its nucleus induces a magnetic moment, μ_m . We compared the latter with a magnetic moment which is created by a current passing through a loop-shaped wire. This magnetic moment is, naturally, larger, the larger the current, I , and the larger the area, A , of the orbit or loop:

$$\mu_m = I \cdot A = \frac{e}{t} \cdot A = \frac{e}{s/v} \cdot A = \frac{evr^2}{2\pi r} = \frac{evr}{2} \quad (15.5)$$

(e is the electron charge, r is the radius of the orbit, $s = 2\pi r$ = length of the orbit, v = velocity of the orbiting electrons, and t = orbiting time).