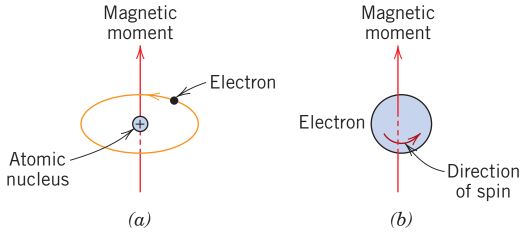

Figure 20.4 Demonstration of the magnetic moment associated with (*a*) an orbiting electron and (*b*) a spinning electron.

charge, an electron may be considered to be a small current loop, generating a very small magnetic field, and having a magnetic moment along its axis of rotation, as schematically illustrated in Figure 20.4*a*.

Each electron may also be thought of as spinning around an axis; the other magnetic moment originates from this electron spin, which is directed along the spin axis as shown in Figure 20.4*b*. Spin magnetic moments may be only in an "up" direction or in an antiparallel "down" direction. Thus each electron in an atom may be thought of as being a small magnet having permanent orbital and spin magnetic moments.

Bohr magneton

The most fundamental magnetic moment is the **Bohr magneton** μ_B, which is of magnitude 9.27×10^{-24} A·m^2. For each electron in an atom the spin magnetic moment is $\pm\mu_B$ (plus for spin up, minus for spin down). Furthermore, the orbital magnetic moment contribution is equal to $m_l\mu_B$, m_l being the magnetic quantum number of the electron, as mentioned in Section 2.3.

In each individual atom, orbital moments of some electron pairs cancel each other; this also holds for the spin moments. For example, the spin moment of an electron with spin up will cancel that of one with spin down. The net magnetic moment, then, for an atom is just the sum of the magnetic moments of each of the constituent electrons, including both orbital and spin contributions, and taking into account moment cancellation. For an atom having completely filled electron shells or subshells, when all electrons are considered, there is total cancellation of both orbital and spin moments. Thus materials composed of atoms having completely filled electron shells are not capable of being permanently magnetized. This category includes the inert gases (He, Ne, Ar, etc.) as well as some ionic materials. The types of magnetism include diamagnetism, paramagnetism, and ferromagnetism; in addition, antiferromagnetism and ferrimagnetism are considered to be subclasses of ferromagnetism. All materials exhibit at least one of these types, and the behavior depends on the response of electron and atomic magnetic dipoles to the application of an externally applied magnetic field.

20.3 DIAMAGNETISM AND PARAMAGNETISM

diamagnetism

Diamagnetism is a very weak form of magnetism that is nonpermanent and persists only while an external field is being applied. It is induced by a change in the orbital motion of electrons due to an applied magnetic field. The magnitude of the induced magnetic moment is extremely small, and in a direction opposite to that of the applied field. Thus, the relative permeability μ_r is less than unity (however, only very slightly), and the magnetic susceptibility is negative; that is, the magnitude of the B field within a diamagnetic solid is less than that in a vacuum. The volume susceptibility χ_m for diamagnetic solid materials is on the order of -10^{-5}. When placed between the poles of a strong electromagnet, diamagnetic materials are attracted toward regions where the field is weak.

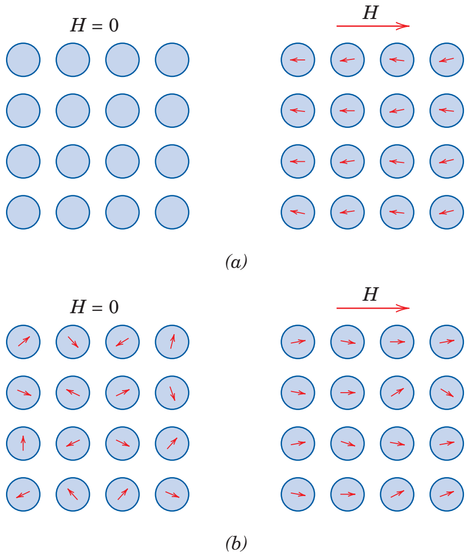

Figure 20.5 (*a*) The atomic dipole configuration for a diamagnetic material with and without a magnetic field. In the absence of an external field, no dipoles exist; in the presence of a field, dipoles are induced that are aligned opposite to the field direction. (*b*) Atomic dipole configuration with and without an external magnetic field for a paramagnetic material.

Figure 20.5*a* illustrates schematically the atomic magnetic dipole configurations for a diamagnetic material with and without an external field; here, the arrows represent atomic dipole moments, whereas for the preceding discussion, arrows denoted only electron moments. The dependence of *B* on the external field *H* for a material that exhibits diamagnetic behavior is presented in Figure 20.6. Table 20.2 gives the susceptibilities of several diamagnetic materials. Diamagnetism is found in all materials, but because it is so weak, it can be observed only when other types of magnetism are totally absent. This form of magnetism is of no practical importance.

paramagnetism

For some solid materials, each atom possesses a permanent dipole moment by virtue of incomplete cancellation of electron spin and/or orbital magnetic moments. In the absence of an external magnetic field, the orientations of these atomic magnetic moments are random, such that a piece of material possesses no net macroscopic magnetization. These atomic dipoles are free to rotate, and **paramagnetism** results when they preferentially align, by rotation, with an external field as shown in Figure 20.5*b*. These magnetic dipoles are acted on individually with no mutual

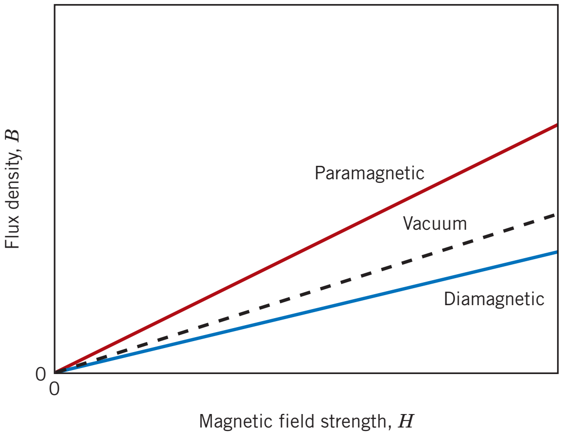

Figure 20.6 Schematic representation of the flux density *B* versus the magnetic field strength *H* for diamagnetic and paramagnetic materials.

Table 20.2 **Room-Temperature Magnetic Susceptibilities for Diamagnetic and Paramagnetic Materials**

Diamagnetics		*Paramagnetics*	
Material	*Susceptibility χ_m (volume) (SI units)*	*Material*	*Susceptibility χ_m (volume) (SI units)*
Aluminum oxide	-1.81×10^{-5}	Aluminum	2.07×10^{-5}
Copper	-0.96×10^{-5}	Chromium	3.13×10^{-4}
Gold	-3.44×10^{-5}	Chromium chloride	1.51×10^{-3}
Mercury	-2.85×10^{-5}	Manganese sulfate	3.70×10^{-3}
Silicon	-0.41×10^{-5}	Molybdenum	1.19×10^{-4}
Silver	-2.38×10^{-5}	Sodium	8.48×10^{-6}
Sodium chloride	-1.41×10^{-5}	Titanium	1.81×10^{-4}
Zinc	-1.56×10^{-5}	Zirconium	1.09×10^{-4}

interaction between adjacent dipoles. Inasmuch as the dipoles align with the external field, they enhance it, giving rise to a relative permeability μ_r that is greater than unity, and to a relatively small but positive magnetic susceptibility. Susceptibilities for paramagnetic materials range from about 10^{-5} to 10^{-2} (Table 20.2). A schematic B-versus-H curve for a paramagnetic material is also shown in Figure 20.6.

Both diamagnetic and paramagnetic materials are considered nonmagnetic because they exhibit magnetization only when in the presence of an external field. Also, for both, the flux density B within them is almost the same as it would be in a vacuum.

20.4 FERROMAGNETISM

ferromagnetism

Certain metallic materials possess a permanent magnetic moment in the absence of an external field, and manifest very large and permanent magnetizations. These are the characteristics of **ferromagnetism,** and they are displayed by the transition metals iron (as BCC α-ferrite), cobalt, nickel, and some of the rare earth metals such as gadolinium (Gd). Magnetic susceptibilities as high as 10^6 are possible for ferromagnetic materials. Consequently, $H \ll M$, and from Equation 20.5 we write

For a ferromagnetic material, relationship between magnetic flux density and magnetization

$$B \cong \mu_0 M \tag{20.8}$$

Permanent magnetic moments in ferromagnetic materials result from atomic magnetic moments due to uncancelled electron spins as a consequence of the electron structure. There is also an orbital magnetic moment contribution that is small in comparison to the spin moment. Furthermore, in a ferromagnetic material, coupling interactions cause net spin magnetic moments of adjacent atoms to align with one another, even in the absence of an external field. This is schematically illustrated in Figure 20.7. The origin of these coupling forces is not completely understood, but it is thought to arise from the electronic structure of the metal. This mutual spin alignment exists over relatively large-volume regions of the crystal called **domains** (see Section 20.7).

domain

saturation magnetization

The maximum possible magnetization, or **saturation magnetization** M_s, of a ferromagnetic material represents the magnetization that results when all the magnetic dipoles in a solid piece are mutually aligned with the external field; there

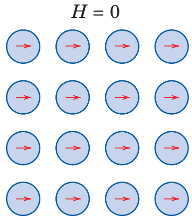

Figure 20.7 Schematic illustration of the mutual alignment of atomic dipoles for a ferromagnetic material, which will exist even in the absence of an external magnetic field.

is also a corresponding saturation flux density B_s. The saturation magnetization is equal to the product of the net magnetic moment for each atom and the number of atoms present. For each of iron, cobalt, and nickel, the net magnetic moments per atom are 2.22, 1.72, and 0.60 Bohr magnetons, respectively.

EXAMPLE PROBLEM 20.1

Saturation Magnetization and Flux Density Computations for Nickel

Calculate **(a)** the saturation magnetization and **(b)** the saturation flux density for nickel, which has a density of 8.90 g/cm^3.

Solution

(a) The saturation magnetization is just the product of the number of Bohr magnetons per atom (0.60 as given earlier), the magnitude of the Bohr magneton μ_B, and the number N of atoms per cubic meter, or

Saturation magnetization for nickel

$$M_s = 0.60\mu_B N \tag{20.9}$$

Now, the number of atoms per cubic meter is related to the density ρ, the atomic weight A_{Ni}, and Avogadro's number N_A, as follows:

For nickel, computation of the number of atoms per unit volume

$$N = \frac{\rho N_A}{A_{Ni}} \tag{20.10}$$

$$= \frac{(8.90 \times 10^6 \text{ g/m}^3)(6.022 \times 10^{23} \text{ atoms/mol})}{58.71 \text{ g/mol}}$$

$$= 9.13 \times 10^{28} \text{ atoms/m}^3$$

Finally,

$$M_s = \left(\frac{0.60 \text{ Bohr magneton}}{\text{atom}}\right)\left(\frac{9.27 \times 10^{-24} \text{ A}\cdot\text{m}^2}{\text{Bohr magneton}}\right)\left(\frac{9.13 \times 10^{28} \text{ atoms}}{\text{m}^3}\right)$$

$$= 5.1 \times 10^5 \text{ A/m}$$

(b) From Equation 20.8, the saturation flux density is just

$$B_s = \mu_0 M_s$$

$$= \left(\frac{4\pi \times 10^{-7} \text{ H}}{\text{m}}\right)\left(\frac{5.1 \times 10^5 \text{ A}}{\text{m}}\right)$$

$$= 0.64 \text{ tesla}$$