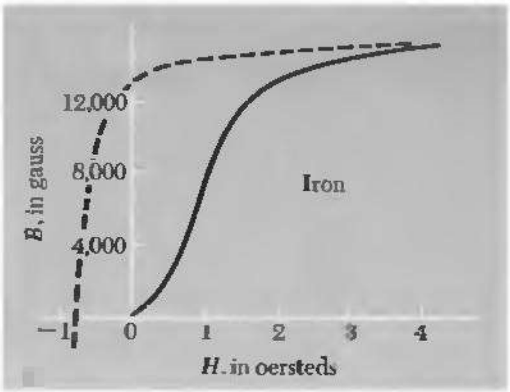
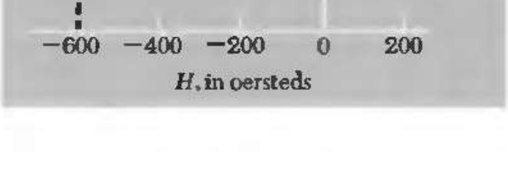


FIGURE 11.31
Magnetization curve for fairly pure iron. The dashed curve is obtained as H is reduced from a high positive value.

FIGURE 11.32
Alnico V is an alloy of aluminum, nickel, and cobalt, which is used for permanent magnets. Compare this portion of its magnetization curve with the corresponding portion of the characteristic for a "soft" magnetic material, shown in Fig. 11.31.



gauss. Instead, when the field H is only a few oersteds, B has risen to thousands of gauss. Of course B and H here refer to an average throughout the whole iron ring; the fine domain structure as such never exhibits itself.

Starting with unmagnetized iron, $B = 0$ and $H = 0$, increasing H causes B to rise in a conspicuously nonlinear way, slowly at first, then more rapidly, then very slowly, finally flattening off. What actually becomes constant in the limit is not B but M. In this graph however, since $M = (B - H)/4\pi$, and $H \ll B$, the difference between B and $4\pi M$ is not appreciable.

The lower part of the B-H curve is governed by the motion of domain boundaries, that is, by the growth of "right-pointing" domains at the expense of "wrong-pointing" domains. In the flattening part of the curve, the atomic moments are being pulled by "brute force" into line with the field. The iron here is an ordinary polycrystalline metal, so only a small fraction of the microcrystals will be fortunate enough to have an easy direction lined up with the field direction.

If we now slowly decrease the current in the coil, thus lowering H, the curve *does not retrace itself*. Instead, we find the behavior given by the dashed curve in Fig. 11.31. This irreversibility is called ***hysteresis***. It is largely due to the domain boundary movements being partially irreversible. The reasons are not obvious from anything we have said, but are well understood by physicists who work on ferromagnetism. The irreversibility is a nuisance, and a cause of energy loss in many technical applications of ferromagnetic materials—for instance, in alternating-current transformers. But it is indispensable for permanent magnetization, and for such applications, one wants to enhance the irreversibility. Figure 11.32 shows the corresponding portion of the B-H curve for a good permanent magnet alloy. Notice that H has to become 600 oersteds in the *reverse* direction before B is reduced to zero. If the coil is simply switched off and removed, we are left with B at 13,000 gauss, called the ***remanence***. Since H is zero, this is essentially the same as the magnetization M, except for the factor 4π. The alloy has acquired a permanent magnetization, that is, one that will persist indefinitely if it is exposed only to weak magnetic fields. All the information that is stored on magnetic tapes and disks owes its permanence to this physical phenomenon.

PROBLEMS

11.1 From the data in Table 11.1 determine the diamagnetic susceptibility of water.

11.2 In Chapter 6 we calculated the field at a point on the axis of a current ring of radius b. (See Eq. 41 of Chapter 6.) Show that for z

$\gg b$ this approaches the field of a magnetic dipole, and find how far out on the axis one has to go before the field has come within 1 percent of the field that an infinitesimal dipole of the same dipole moment would produce at that point.

11.3 How large is the magnetic moment of 1 gm of liquid oxygen in a field of 18 kilogauss, according to the data in Table 11.1? Given that the density of liquid oxygen is 0.85 gm/cm^3 at 90 K, what is its magnetic susceptibility χ_m?

11.4 At the north magnetic pole the earth's magnetic field is vertical and has a strength of 0.62 gauss. The earth's field at the surface and further out is approximately that of a central dipole.

(*a*) What is the magnitude of the dipole moment in ergs/gauss?

(*b*) In joules/tesla?

(*c*) Imagine that the source of the field is a current ring on the "equator" of the earth's metallic core, which has a radius of 3000 km, about half the earth's radius. How large would the current have to be?

11.5 A solenoid like the one described in Section 11.1 is located in the basement of a physics laboratory. A physicist on the top floor of the building, 60 feet higher and displaced horizontally 80 feet, complains that its field is disturbing his measurements. Assuming that the solenoid is operating under the conditions described, and treating it as a simple magnetic dipole, compute the field strength at the location of the complaining physicist. Comment, if you see any grounds for doing so, on the merit of his complaint.

11.6 A cube of magnetite 5 cm on an edge is magnetized to saturation in a direction perpendicular to two of its faces. Find the magnitude in amperes of the ribbon of bound-charge current that flows around the circuit consisting of the other four faces of the cube. The saturation magnetization in magnetite is 4.8×10^5 joules/tesla-m^3. Would the field of this cubical magnet seriously disturb a compass 2 meters away?

11.7 A sphere of radius R carries the charge Q which is distributed uniformly over the surface of the sphere with the density $\sigma = Q/4\pi R^2$. This shell of charge is rotating about an axis of the sphere with the angular velocity ω, in radians/sec. Find its magnetic moment. (Divide the sphere into narrow bands of rotating charge; find the current to which each band is equivalent, and its dipole moment, and integrate over all bands.)

Ans. $QR^2\omega/3c$.

11.8 Show that the work done in pulling 1 gm of paramagnetic material from a region where the magnetic field strength is B to a region where the field strength is negligibly small is $\frac{1}{2}\chi B^2$, χ being the specific susceptibility. Then calculate exactly how much work, per gram, would be required to remove the liquid oxygen from the position referred to in Sec. 11.1. (Of course, this only applies if χ is a constant over the range of field strengths involved.)

11.9 A cylindrical solenoid has a single-layer winding of radius r_0. It is so long that near one end the field may be taken to be that of a semi-infinite solenoid. Show that the point on the axis of the solenoid where a small paramagnetic sample will experience the greatest force is located a distance $r_0/\sqrt{15}$ in from the end.

11.10 In the case of an electric dipole made of two charges Q and $-Q$ separated by a distance s, the volume of the near region, where the field is essentially different from the ideal dipole field, is proportional to s^3. The field strength in this region is proportional to Q/s^2, at similar points as s is varied. The dipole moment $p = Qs$, so that if we shrink s while holding p constant, the product of volume and field strength does what? Carry through the corresponding argument for the magnetic field of a current loop. The moral is: If we are concerned with the space average field in any volume containing dipoles, the essential difference between the insides of electric and magnetic dipoles *cannot* be ignored, even when we are treating the dipoles otherwise as infinitesimal.

11.11 Write out Maxwell's equations as they would appear if we had magnetic charge and magnetic charge currents as well as electric charge and electric currents. Invent any new symbols you need and define carefully what they stand for. Be particularly careful about + and − signs.

11.12 We want to find the energy required to bring two dipoles from infinite separation into the configuration shown in (*a*) below, defined by the distance apart r and the angles θ_1 and θ_2. Both dipoles lie in the plane of the paper. Perhaps the simplest way to compute the energy is this: Bring the dipoles in from infinity while keeping them in the orientation shown in (*b*). This takes no work, for the force on each dipole is zero. Now calculate the work done in rotating $\mathbf{m}_1$ into

PROBLEM 11.12