

The metal lead is a moderately good conductor at room temperature. Its resistivity, like that of other pure metals, varies approximately in proportion to the absolute temperature. As a lead wire is cooled to 15 K its resistance falls to about 1/20 of its value at room temperature, and the resistance continues to decrease as the temperature is lowered further. But as the temperature 7.22 K is passed, there occurs without forewarning a startling change: the electrical resistance of the lead wire vanishes! So small does it become that a current flowing in a closed ring of lead wire colder than 7.22 K – a current that would ordinarily die out in much less than a microsecond – will flow for *years* without measurably decreasing. This phenomenon has been directly demonstrated. Other experiments indicate that such a current could persist for billions of years. One can hardly quibble with the flat statement that the resistivity is zero. Evidently something quite different from ordinary electrical conduction occurs in lead below 7.22 K. We call it *superconductivity*.

Superconductivity was discovered in 1911 by the great Dutch low-temperature experimenter Kamerlingh Onnes. He observed it first in mercury, for which the critical temperature is 4.16 K. Since then hundreds of elements, alloys, and compounds have been found to become superconductors. Their individual critical temperatures range from roughly a millikelvin up to the highest yet discovered, 138 K. Curiously, among the elements that do *not* become superconducting are some of the best normal conductors such as silver, copper, and the alkali metals.

Superconductivity is essentially a quantum-mechanical phenomenon, and a rather subtle one at that. The freely flowing electric current consists of electrons in perfectly orderly motion. Like the motion of an electron in an atom, this electron flow is immune to small disturbances – and for

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a similar reason: a finite amount of energy would be required to make any change in the state of motion. It is something like the situation in an insulator in which all the levels in the valence band are occupied and separated by an energy gap from the higher energy levels in the conduction band. But unlike electrons filling the valence band, which must in total give exactly zero net flow, the lowest energy state of the superconducting electrons can have a net electron velocity, hence current flow, in some direction. Why should such a strange state become possible below a certain critical temperature? We can't explain that here.¹ It involves the interaction of the conduction electrons not only with each other, but also with the whole lattice of positive ions through which they are moving. That is why different substances can have different critical temperatures, and why some substances are expected to remain normal conductors right down to absolute zero.

In the physics of superconductivity, magnetic fields are even more important than you might expect. We must state at once that the phenomena of superconductivity *in no way* violate Maxwell's equations. Thus the persistent current that can flow in a ring of superconducting wire is a direct consequence of Faraday's law of induction, given that the resistance of the ring is really zero. For if we start with a certain amount of flux Φ_0 threading the ring, then because $\int \mathbf{E} \cdot d\mathbf{s}$ around the ring remains always zero (otherwise there would be infinite current due to the zero resistance), $d\Phi/dt$ must be zero. The flux cannot change; the current I in the ring will automatically assume whatever value is necessary to maintain the flux at Φ_0 . Figure I.1 outlines a simple demonstration of this, and shows how a persistent current can be established in an isolated superconducting circuit.

Superconductors can be divided into two types. In Type 1 superconductors, the magnetic field inside the material itself (except very near the surface) is always zero. That is *not* a consequence of Maxwell's equations, but a property of the superconducting state, as fundamental, and once as baffling, a puzzle as the absence of resistance. The condition $\mathbf{B} = 0$ inside the bulk of a Type 1 superconductor is automatically maintained by currents flowing in a thin surface layer. In Type 2 superconductors, quantized magnetic flux tubes may exist for a certain range of temperature and external magnetic field. These tubes are surrounded by vortices of current (essentially little solenoids) which allow the magnetic field to be zero in the rest of the material. Outside the flux tubes the material is superconducting.

A strong magnetic field destroys superconductivity, although Type 2 superconductors generally can tolerate much larger magnetic fields than

¹ The abrupt emergence of a state of order at a certain critical temperature reminds us of the spontaneous alignment of electron spins that occurs in iron below its Curie temperature (mentioned in Section 11.11). Such *cooperative* phenomena always involve a large number of mutually interacting particles. A more familiar cooperative phenomenon is the freezing of water, also characterized by a well-defined critical temperature.

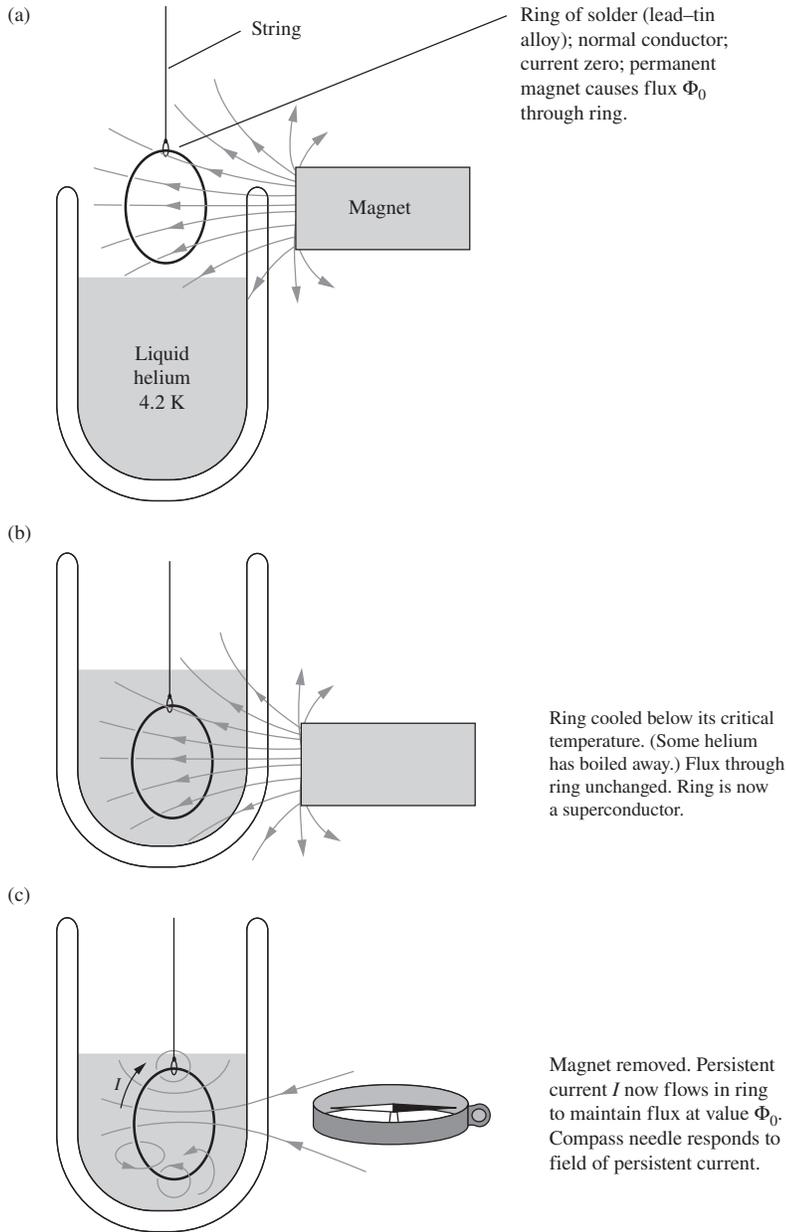


Figure I.1. Establishing a persistent current in a superconducting ring. The ring is made of ordinary solder, a lead-tin alloy. (a) The ring, not yet cooled, is a normal conductor with ohmic resistance. Bringing up the permanent magnet will induce a current in the ring that will quickly die out, leaving the magnetic flux from the magnet, in amount Φ , passing through the ring. (b) The helium bath is raised without altering the relative position of the ring and the permanent magnet. The ring, now cooled below its critical temperature, is a superconductor with resistance zero. (c) The magnet is removed. The flux through the zero resistance ring cannot change. It is maintained at the value Φ by a current in the ring that will flow as long as the ring remains below the critical temperature. The magnetic field of the persistent current can be demonstrated with the compass.

Type 1. None of the superconductors known before 1957 could stand more than a few hundred gauss. That discouraged practical applications of zero-resistance conductors. One could not pass a large current through a superconducting wire because the magnetic field of the current itself would destroy the superconducting state. But then a number of Type 2 superconductors were discovered that could preserve zero resistance in fields up to 10 tesla or more. A widely used Type 2 superconductor is

an alloy of niobium and tin that has a critical temperature of 18 K and if cooled to 4 K remains superconducting in fields up to 25 tesla. Type 2 superconducting solenoids are now common that produce steady magnetic fields of 20 tesla without any cost in power other than that incident to their refrigeration. Uses of superconductors include magnetic resonance imaging (MRI) machines (which are based on the physics discussed in Appendix J) and particle accelerators. There are also good prospects for the widespread use of superconductors in large electrical machinery, maglev trains, and the long-distance transmission of electrical energy.

In addition to the critical magnetic field, the critical temperature is also a factor in determining the large-scale utility of a superconductor. In particular, a critical temperature higher than 77 K allows relatively cheap cooling with liquid nitrogen (as opposed to liquid helium at 4 K). Prior to 1986, the highest known critical temperature was 23 K. Then a new type of superconductor (a copper oxide, or *cuprate*) was observed with a critical temperature of 30 K. The record critical temperature was soon pushed to 138 K. These superconductors are called *high-temperature superconductors*. Unfortunately, although they are cheaper to cool, their utility is limited because they tend to be brittle and hence difficult to shape into wires. However, in 2008 a new family of high-temperature superconductors was discovered, with iron as a common element. This family is more ductile than cuprates, but the highest known critical temperature is 55 K. The hope is that this will eventually cross the 77 K threshold.

The mechanism that leads to high-temperature superconductivity is more complex than the mechanism for low-temperature superconductivity. In contrast with the well-established BCS theory (named after Bardeen, Cooper, and Schrieffer; formulated in 1957) for low-temperature superconductors, a complete theory of high-temperature superconductors does not yet exist. All known high-temperature superconductors are Type 2, but not all Type 2 superconductors are high-temperature. Indeed, *low-temperature* Type 2 superconductors (being both ductile and tolerant of large magnetic fields) are the ones presently used in MRI machines and other large-scale applications.

At the other end of the scale, the quantum physics of superconductivity makes possible electrical measurements of unprecedented sensitivity and accuracy – including the standardization of the volt in terms of an easily measured oscillation frequency. To the physicist, superconductivity is a fascinating large-scale manifestation of quantum mechanics. We can trace the permanent magnetism of the magnet in Fig. I.1 down to the intrinsic magnetic moment of a spinning electron – a kind of supercurrent in a circuit less than 10^{-10} m in size. The ring of solder wire with the persistent current flowing in it is, in some sense, like a gigantic atom, the motion of its associated electrons, numerous as they are, marshaled into the perfectly ordered behavior of a single quantum state.