Resistance in High-Temperature Superconductors

Researchers are beginning to see how the motion of magnetic vortices in these materials can interfere with the flow of current

by David J. Bishop, Peter L. Gammel and David A. Huse

Levitating trains and high-capacity devices for storing electrical energy were among the many bold visions some physicists entertained after the discovery of high-temperature superconductors in 1986. But several difficulties quickly emerged to temper the promise extended by the ability of these ceramic materials to conduct electricity at high temperatures without resistance. One of the most vexing hindrances has been the destruction of the superconducting state when the material is placed in a magnetic field—a condition crucial for, or at least inescapable in, many envisaged applications. Resistance to current flow can happen when the external magnetic field penetrates the superconductor in the form of discrete bundles called flux lines. Because a line of flux consists of whirlpools of electric current, it is often called a vortex. If these vortices move, they can impede the flow of electrons. Knowing how these vortices move and arrange themselves under various temperature and magnetic-field conditions will be critical in controlling the phenomenon and in maintaining the supercurrent flow.

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Fortunately, recent studies have greatly enhanced our knowledge of vortices. Investigators have found that the magnetic-field behavior of superconductors is much richer than formerly thought. Indeed, the vortices have been found to be capable of forming a number of exotic new phases of matter within the family of high-temperature superconductors. To describe these phases—vortex solids, liquids and glasses—workers have been forced to discard some previously held views in superconductivity and to form fresh hypotheses based on modern concepts in condensed-matter physics. To test the new ideas, investigators have devised experimental techniques of unprecedented sensitivity. The work may ultimately point the way to full understanding and, perhaps, to effective use of these new materials.

In retrospect, one should not be surprised that the knowledge of the superconducting state gathered before 1986 was inadequate to describe high-temperature superconductivity. The early ideas evolved from observations of conventional superconductors. Such materials, generally familiar metals and alloys, conduct electricity without resistance only when cooled to temperatures within a few degrees of absolute zero. In fact, curiosity about the behavior of matter at low temperatures had led the Dutch physicist Heike Kamerlingh Onnes to discover superconductivity in 1911. The finding came about because Onnes had accomplished the experimentally daunting task of liquefying helium, the last of the inert gases to be condensed. Liquid helium enabled Onnes to cool down materials to temperatures near one kelvin of absolute zero. (Absolute zero is equal to –458 degrees Fahrenheit or –273 degrees Celsius.)

According to a perhaps apocryphal story, the finding emerged when Onnes asked a student to measure the electrical resistance of mercury. The student reported that the resistance disappeared when the temperature of the sample fell to 4.2 kelvins. Onnes sent him back to the laboratory to find what Onnes thought was an "error" producing an experimental artifact. After several tries, the error could not be found, and the workers realized they had made a historic discovery. Onnes went on to win the 1913 Nobel Prize in Physics for this and many other important discoveries in low-temperature physics.

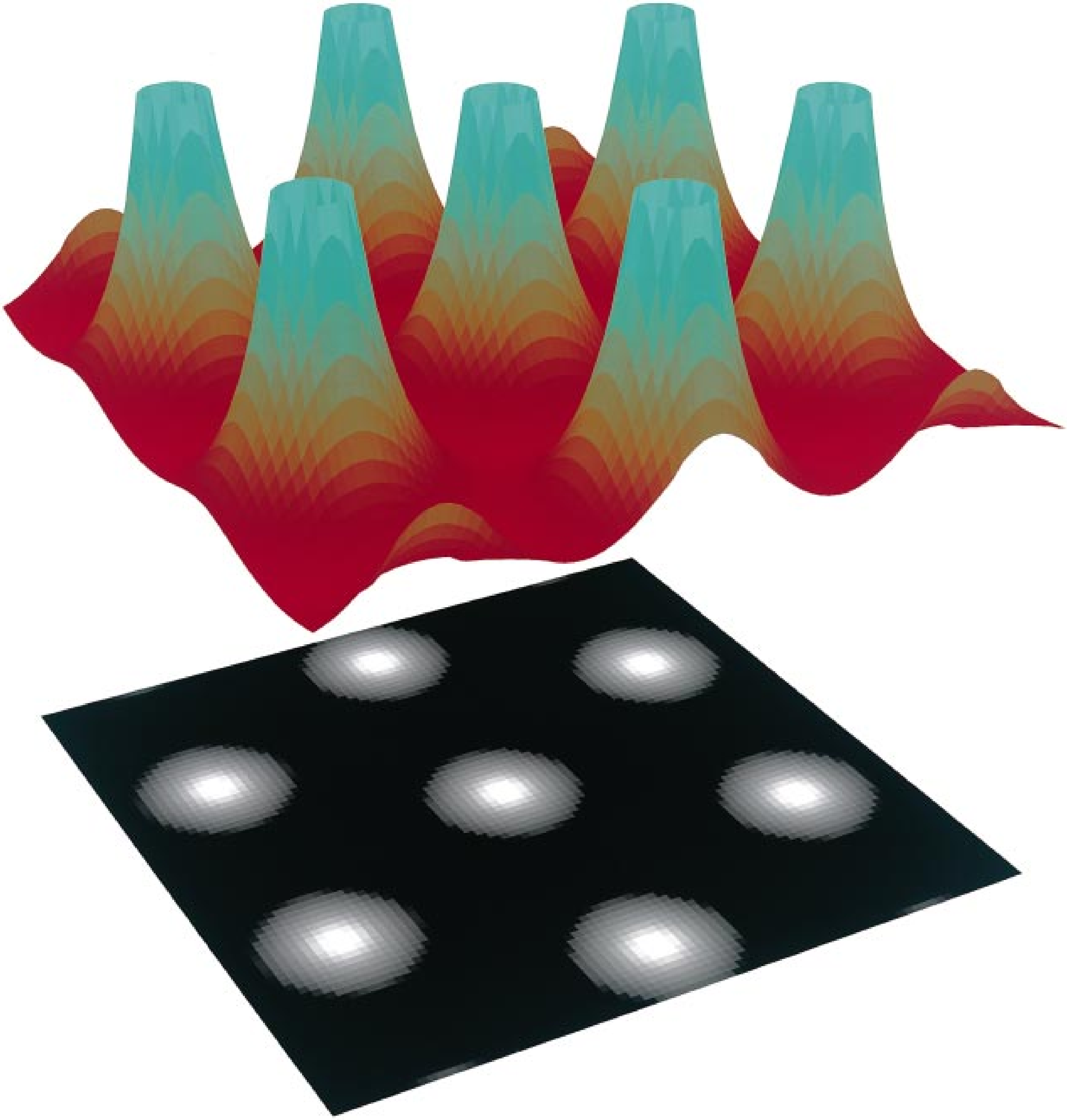
Zero resistance to current flow was not the only reason for amazement. The behavior of superconductors in a magnetic field proved equally astounding. In 1933 two German physicists, Walther Meissner and Robert Ochsenfeld, found that a superconductor can

VORTICES, represented here as green-and-red volcanolike tubes, are discrete bundles of magnetic-field lines that pierce a superconductor. The computer image represents the strength of the magnetic field (plotted as the height of the tubes) across the surface of the sample. The field is largest at the center of each vortex. The projection below the image depicts the vortices as white dots and shows that they form a regular, triangular pattern within the body of the superconductor.

expel magnetic fields when cooled below its superconducting transition temperature. The complete expulsion of a magnetic field is now known as the Meissner effect. Along with the absence of resistance, the ability to exclude magnetic fields propels the enormous research interest in superconductivity.

At this juncture, observation had far outrun theory. The quantum models developed in the 1930s could account for the conductivity in normal metals, but they could not explain the superconducting state. The problem proved particularly intractable; workers did not achieve significant theoretical understanding of the microscopic origins of superconductivity until the 1950s. Then, two Russians, Vitaly L. Ginzburg and Lev D. Landau, developed a phenomenological theory. By looking at what happens during the transition from the normal state to the superconducting one, the scientists were able to formulate a series of equations that could describe the phenomenon. They could not, however, explain why it occurred.

In 1957 John Bardeen, Leon N. Cooper and J. Robert Schrieffer developed



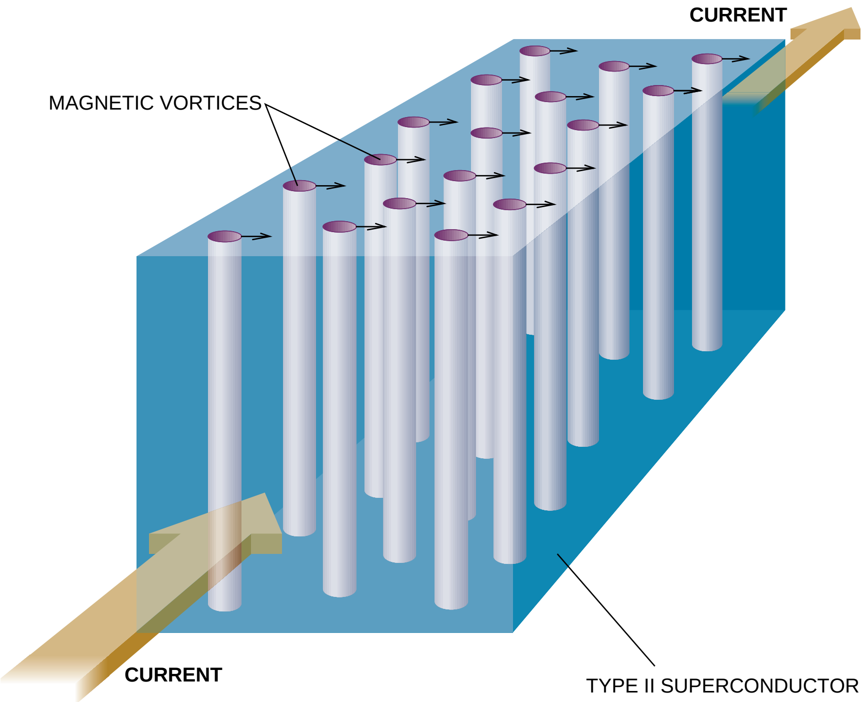
the theory that provided the microscopic explanation for superconductivity. According to the so-called BCS theory, the conduction electrons travel without meeting resistance because they move in pairs, known as Cooper pairs. Electrons form Cooper pairs because they interact with phonons, mechanical vibrations in the crystalline lattice of the metal that resemble sound waves. The movement of the atoms in the lattice tends to neutralize the repulsion that electrons normally have for one another. In fact, it actually produces a small attractive force between electrons. The effectiveness of this interaction depends sharply on temperature. Indeed, the point on a thermal scale at which superconductivity appears is called the transition temperature. At temperatures above this critical point, thermal fluctuations destroy the Cooper pairs and, consequently, the superconductivity of the metal.

The pairing interaction determines two important microscopic distance scales in a superconductor. The first of these is the spatial separation of the electrons in a Cooper pair. This distance is referred to as the coherence length. It is the smallest length in a superconductor over which electronic properties, such as the local resistivity, can change. In typical superconductors the coherence length ranges from hundreds to thousands of angstroms. (These scales of distance are related to atomic reality and so can can be difficult to grasp intuitively—one angstrom equals 10^{-10} meter. The atoms in most materials are spaced one to three angstroms apart.)

The second microscopic characteristic length is related to the strength of the Meissner effect—that is, the ability of a superconductor to expel an applied magnetic field. The effect occurs when a small magnetic field is applied to a superconductor, creating currents that flow near the surface of the material. These induced currents create a magnetic field that precisely cancels the applied field in the rest of the material. The magnitude of these induced currents falls off exponentially with increasing distance from the surface of the superconductor. The length over which this decay occurs is called the magnetic penetration depth. This depth is the shortest distance over which the magnetic field can change in a superconductor. In typical superconductors, this length can vary from hundreds up to tens of thousands of angstroms.

These microscopic lengths define two broadly different categories of superconductors. In type I superconductors the coherence length is longer than the penetration depth. These materials tend to be low-temperature, low-field superconductors. If the field reaches a critical strength (which varies from substance to substance), it enters the material, destroying the superconducting state. Because their lack of resistance disappears at relatively low fields, type I superconductors have little potential for applications or interesting technologies.

Type II superconductors are much more useful. The penetration depth of such superconductors is longer than the coherence length. As a result, they remain superconducting even after the magnetic field enters. Type II superconductors can withstand high fields—up to what is called the upper critical field—and thus can carry the largest currents. All the technologically interesting superconductors, including the known high-temperature materials, are of this type.



CURRENT FLOW through a superconductor (*blue rectangular box*) can be disrupted by vortices (*cylinders*). Each vortex consists of a ring of circulating current induced by an external magnetic field (*not shown*). The applied current adds to the circulating current on one side of the vortex but subtracts from the other. The net result is a force that pushes the vortices at right angles to the current flow; the movement dissipates energy and produces resistance.

In the 1950s the Russian physicist Alexei A. Abrikosov published the basic theory of how a conventional type II superconductor behaves in a magnetic field. Building on the work of Ginzburg and Landau, he showed that the magnetic response of a type II superconductor below the critical temperature depends on the strength of the applied field and on the temperature. Such a relation can be represented by a magnetic phase diagram [*see illustration on page 52*], which shows that a conventional superconductor has three distinct magnetic states.

The first one is simply the Meissner state—that is, the state in which the material fully expels the applied field. The superconductor exists in this state as long as the applied magnetic field remains below a certain strength. This field, called the lower critical field, in general depends on temperature.

The second state emerges if the applied field increases to a value higher than the lower critical field. At this point, the magnetic field can still penetrate the superconductor but not completely or uniformly. Instead discrete flux lines, forming tubular intrusions of the applied field, pierce the sample. The quantum mechanics of the superconductor requires that each flux line have exactly the same magnitude. This unit of flux is known as the flux quantum. Because each flux line must have the same strength, any change in the applied magnetic field must change the density of the flux lines. In other words, as the field varies, the distance between the lines changes in response. The mini-

Visualizing the Superconducting Flux Lattice

As children, we all "decorated" the magnetic-field lines of a permanent magnet by using a piece of paper and iron filings. Some of us are still doing it. Specifically, we can decorate the magnetic field that can permeate a superconductor. A small magnetic field enters the superconductor in discrete bundles called flux or vortex lines. The lines arrange themselves in a regular pattern. Several techniques, including neutron scattering and scanning tunneling microscopy, can reveal the pattern, but magnetic decoration is perhaps the simplest and most direct.

The decoration apparatus (*a*), about 10 centimeters high and three centimeters in diameter, consists of only a few key components. The superconductor to be studied rests inside a vacuum can filled with helium gas. We apply a magnetic field with the coils and cool the sample to below its transition temperature. We then heat up the tungsten filament, which has a blob of iron attached to it. The iron particles evaporate. The helium gas in the can cools the iron particles, producing a slowly drifting magnetic "smoke." The iron particles in the smoke are quite small, about 100 angstroms in diameter. They drift around the baffle, which protects the sample from the heat, to the surface of the superconductor. There they decorate the regions where the magnetic-flux lines pass through the surface. The iron particles "stick" to the surface because of the slight attractive forces that exist between all particles. This attraction, called the van der Waals force, acts as an "atomic glue." The sample can warm up to room temperature and still retain the iron particles. We can then use an electron microscope to form a direct picture of the iron particles, which replicates the original flux lattice pattern.

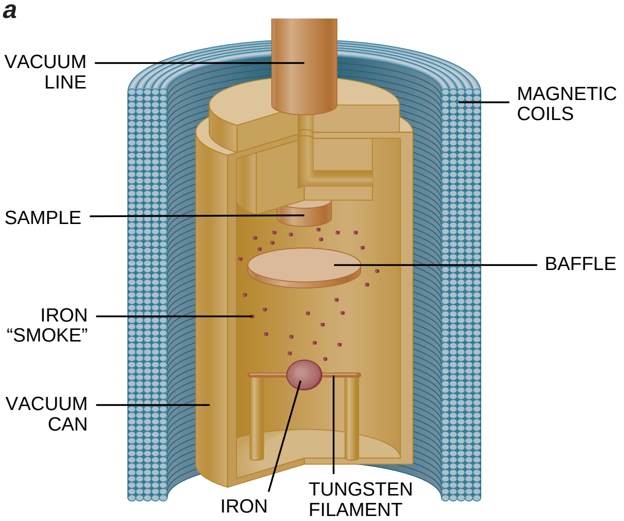
The flux lines appear as dots, revealing the well-ordered nature of the lattice (a photograph of the vortex lattice is on page 53). From such pictures, investigators can determine the amount of magnetic flux per flux line. This amount is a fundamental constant for superconductors known as the flux quantum, Φ_0. For all known superconductors, $\Phi_0 = hc/2e$, where h is Planck's constant, c is the speed of light and e is the charge on the electron. The "2" in the denominator is a direct consequence of the fact that the electrons in superconductors travel in pairs. In the early days of high-temperature superconductivity, some researchers thought the flux quantum might have a different value for these materials. Experiments such as these, which simply count the number of flux lines, quickly ruled out that possibility. By counting, one can show that the ratio of the applied magnetic field to the density of flux lines is equal to the flux quantum.

Decoration experiments have enabled us to see many other novel structures. The pattern of the flux lines will be different if the applied magnetic field strikes the sample at an angle with respect to a major crystallographic axis. Instead of a regular lattice, flux chains appear (*b*).

Several kinds of quantitative analysis are possible with such images. After the locations of the flux lines are digitized, a computer can draw in lines between all of the points in the flux lattice (*c*). In a perfect triangular lattice, each flux line has six nearest neighbors. The defects in the lattice appear as flux lines with different numbers of nearest neighbors. The defects have been shaded red.

Such decorations show that the superconducting flux lattice can take on a specific type of pattern called hexatic order. In such ordered structures the positions of the particles can be random, but the bond angles between nearest neighbors are similar. For the triangulation pattern shown, the bond angles are roughly the same from one end of the picture to the other. But because of the defects, the particles are spaced evenly only over short distances. The easiest way to see this bond-angle order is to place the edge of the page near your eye and to sight along the rows.

a



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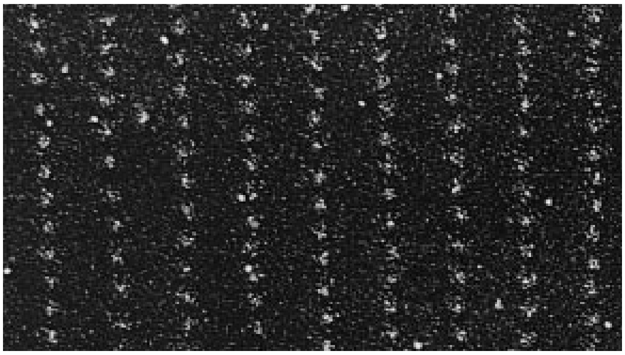

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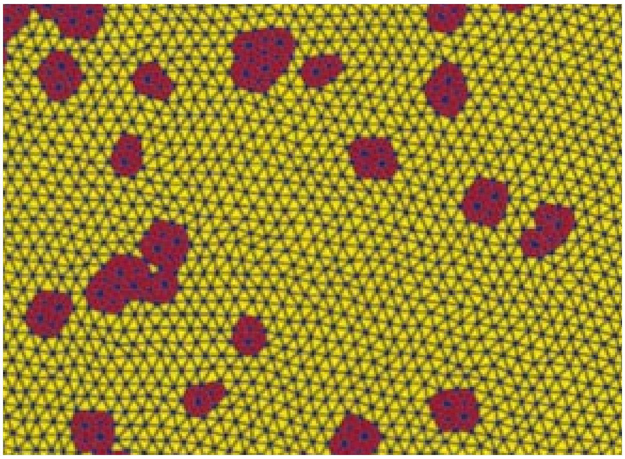
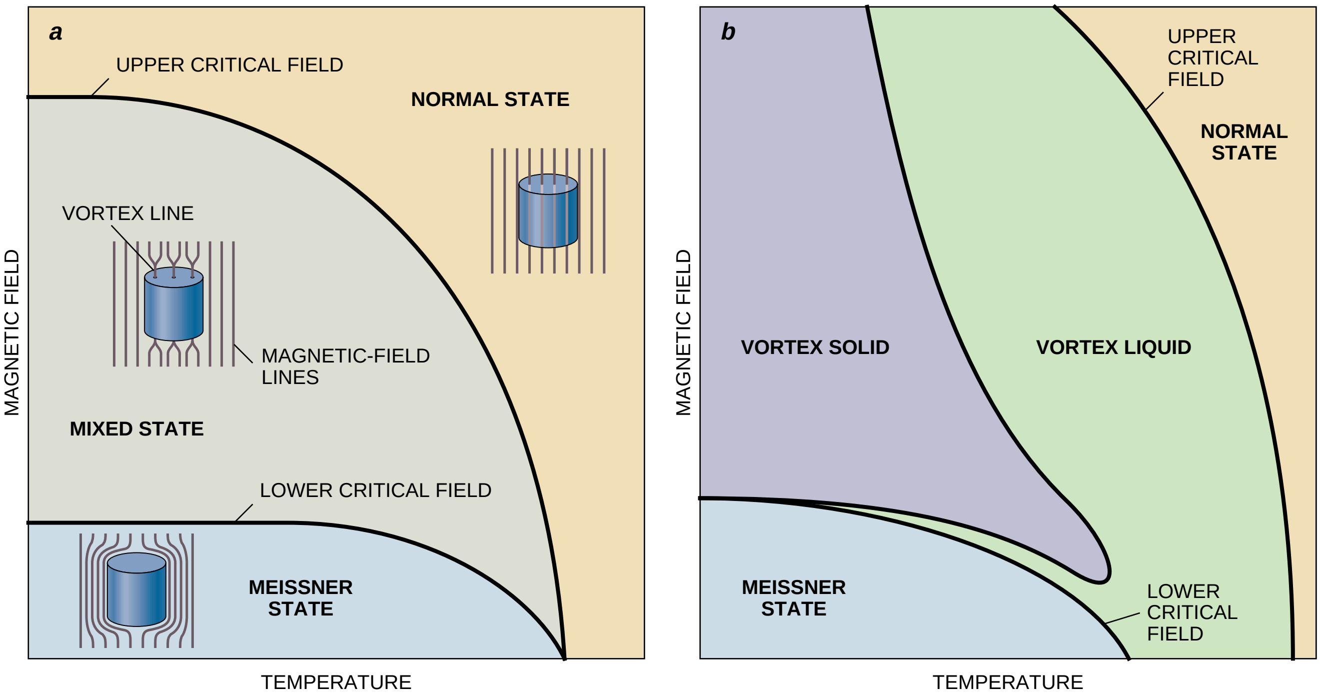




MAGNETIC PHASE DIAGRAMS show what happens when a type II superconductor is immersed in a magnetic field. Diagram *a* depicts the three phases present in a conventional superconductor. In the Meissner state (*lower left*) the applied field is expelled. In the mixed (or vortex solid) state the field penetrates in discrete bundles, or vortex lines. In the normal state the field destroys superconductivity and penetrates the material uniformly. Diagram *b* shows that high-temperature superconductors have similar phases, except for a vortex liquid regime. This state exists because thermal fluctuations melt the vortex solid, which is either a lattice (for clean superconductors) or a glass (for dirty ones).

mum energy configuration for such an array of flux lines (as seen from a bird's-eye view above the surface) is a triangular lattice.

The structure of an individual flux line depends on the coherence length and penetration depth. Each line has a small core. The diameter of the core depends on the coherence length. Inside the core, the material is a normal metal. Circulating around the core are supercurrents. (This circulating current is the reason physicists call the core a vortex line.) These supercurrents produce a magnetic field, and the distance over which this magnetic field persists is the magnetic penetration depth. Researchers can make the vortices visible by using small magnetic particles [*see box on preceding page*]. In such images the very well ordered triangular lattice becomes apparent.

The third and final magnetic state of a superconductor emerges if the applied field reaches a second, higher critical point. Above this upper critical field, the superconductivity is completely destroyed, restoring the material to its normal state. The destruction occurs because increases in the strength of the magnetic field force the vortex lines closer together. When the vortex cores, which behave as normal metals, overlap too much, there is no longer enough room between the vortices to maintain superconductivity.

The descriptions of the three magnetic states seemed to detail sufficiently well the effects of an applied magnetic field on superconductors. Then, in 1986, J. Georg Bednorz and K. Alex Müller of the IBM Zürich Research Center came across a new class of type II superconductor. These materials, a family of copper oxide ceramics, were found in some cases to superconduct at a temperature that exceeded 120 kelvins. In contrast, the highest critical temperatures for conventional superconductors lie in the range of 20 to 25 kelvins. The high-temperature superconductors galvanized the scientific world because the materials could easily be cooled with liquid nitrogen, which in bulk costs less than 10 cents per liter (compared to $5 a liter for liquid helium). Even small laboratory-grade refrigerators can cool below the transition temperature of the new superconductors.

As exciting as the high critical temperatures were, a disturbing fact came to light when their properties were studied as a function of an applied magnetic field. Specifically, the high-temperature superconductors did not conform to Abrikosov's successful model. The discrepancies were discovered when investigators studied the materials in magnetic fields that would be necessary in technological use. The strengths of the fields range up to about 10 teslas (a tesla is roughly 20,000 times the strength of the earth's magnetic field). In these fields the resistance of some of these materials did not fall below that of ordinary copper wire until the temperature dropped to only 20 to 30 percent of the superconducting transition temperature. In certain cases, the resistance of some materials in a field remained 100 times higher than that of copper. The advantages of a high-temperature superconductor seemed lost. Additional experiments uncovered the reason. The vortex lines were behaving in an unusual way: they were not always arranging themselves in a rigid, triangular lattice. Instead researchers found that the vortex lattice could "melt" into a liquidlike state. This behavior was suppressing the material's transition to superconductivity.

There are a variety of reasons why this novel state of matter, a vortex liquid, should hinder current flow in the high-temperature superconductors. Perhaps the most convenient way to understand the effect is to imagine vortex lines in a superconductor as rubber bands. Vortex lines and rubber bands tend to stay short, because making a line longer or stretching a rubber band costs energy. Thermal fluctuations, however, oppose that tendency. Such fluctuations make the atoms in a solid and the vortex lines vibrate with a larger amplitude as the temperature rises. The vortex lines then “stretch.” The energy in a vortex line tries to restore the line to its unstretched state.

This restoring force is a function of the coherence length and penetration depth. Long coherence lengths or short penetration depths produce a good deal of restoring force and limit the thermal vibrations of the vortex lines. Most ordinary type II superconductors have such characteristics. The restoring force dominates, keeping the lines straight and short. Thus, thermal fluctuations of the vortex lines are small.

On the other hand, high-temperature superconductors have virtually the opposite characteristics: the coherence lengths are short and the penetration depths long. The coherence length is sometimes as short as a few angstroms, which is about 10 to 100 times below that of conventional superconductors. The penetration depth of high-temperature superconductors ranges from 1,000 to more than 100,000 angstroms; the values exceed that of many conventional superconductors by a factor of 10 to 100.

Coupled with the high transition temperatures, the extreme values of the coherence lengths and penetration depths mean that large thermal fluctuations of the vortex lines occur in the high-temperature superconductors. Indeed, at sufficiently high temperatures the lines vibrate enough to “melt” the vortex lattice. The phenomenon is similar to the way that the thermal vibrations of water molecules can cause ice to melt into water. For some high-temperature materials, the vortex liquid state persists over a temperature range wider than that of the lattice state.

Why does a vortex liquid affect the resistance of the superconductor? The answer lies in thinking about what happens when a current is sent through a type II superconductor in an applied magnetic field. Recall that each vortex line consists of flowing currents circulating around a normal (nonsuperconducting) core. When an applied current flows through the sample, it adds to the circulating current on one side of the vortex and subtracts from it on the other side. As a result, a force acts on the vortex line. The force tends to make the vortex move in a direction at right angles to both the vortex line and the applied current. This force is the Magnus force. It is similar to the lift generated by an airplane wing, a situation in which air flows faster over the upper surface of the wing than it does over the lower surface. If vortex lines move in response to the Magnus force, they will dissipate the energy in the flowing current. Specifically, the dissipation induces a voltage and thus resistance in a sample.

Measurement of this resistance shows how the vortex liquid behaves like ordinary water near the melting point. We have explored the resistance of a very clean piece of the high-temperature superconductor YBa$_2$Cu$_3$O$_7$ (yttrium-barium2-copper3-oxygen7, which is often shortened to YBCO, pronounced “ibco”) as a function of temperature in a fixed magnetic field. At high temperatures (that is, in the vortex liquid phase), the resistance indicated by the data is high. Lowering the temperature froze the vortex liquid into the vortex lattice state. Hence, the lines were no longer free to move, and the resistance disappeared.

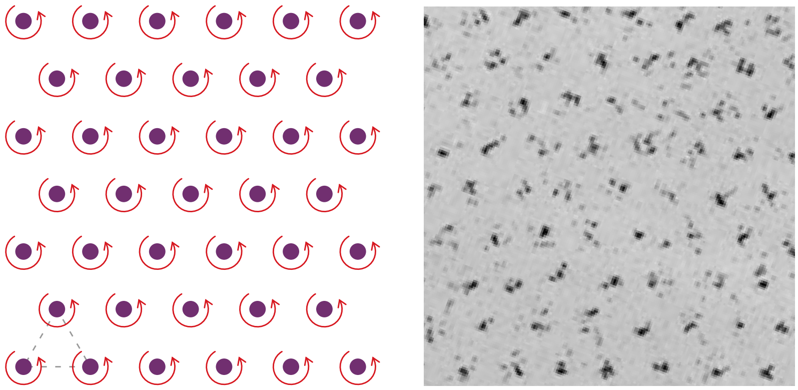
Such resistance measurements also showed that the vortex liquid is slightly supercooled before it freezes. The phenomenon resembles what one finds in clean water, where the liquid phase can to some extent persist below the freezing point. Supercooling can be expressed more technically: the behavior of the substance on heating does not precisely retrace that found on cooling [*see illustration on page 55*]. These processes are said to be hysteretic.

Yet insight into how the vortex liquid state behaves and freezes into a lattice leaves open a question essential for applications. The vortex liquid freezes into a regular lattice only if the material is clean. But what happens when the superconductor is “dirty”—that is, if chemical impurities and defects reside in the atomic lattice?

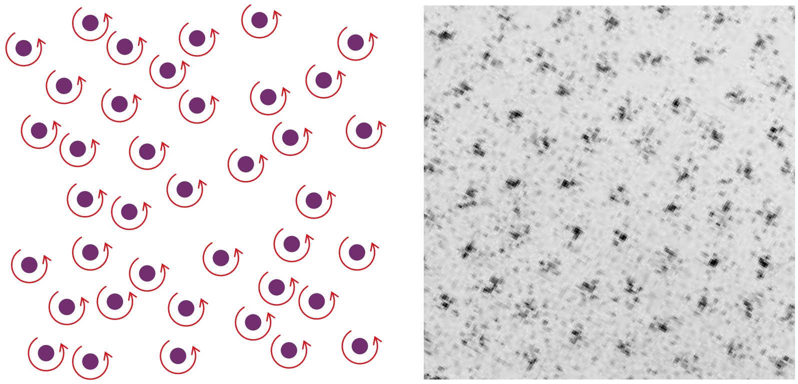
The question is not trivial. Supercon-

States of a Vortex Solid

A superconductor in a magnetic field “freezes” solid in two ways. If the material is clean, the vortex lines will fall into a regular triangular array, forming a vortex lattice. If the substance has many defects or impurities, the lines will develop a disordered pattern, forming a vortex glass.



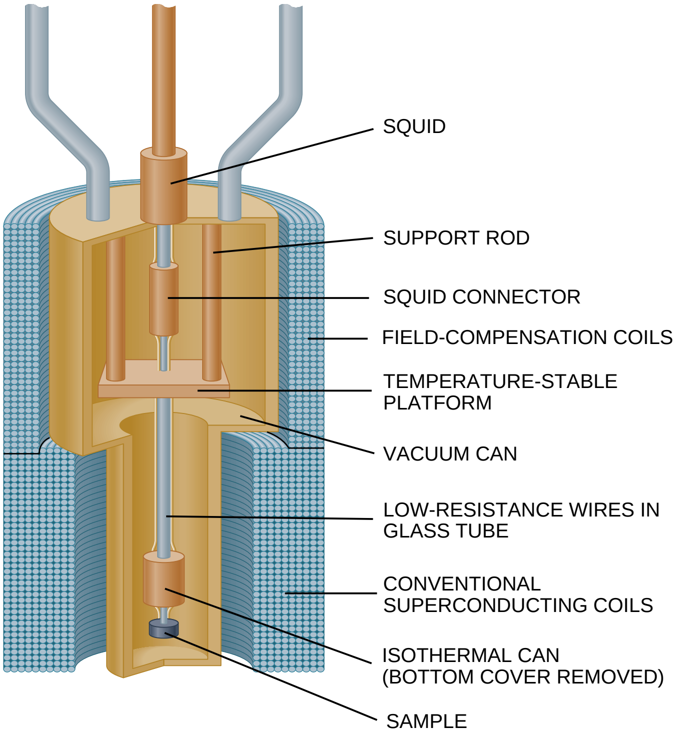
VORTEX LATTICE

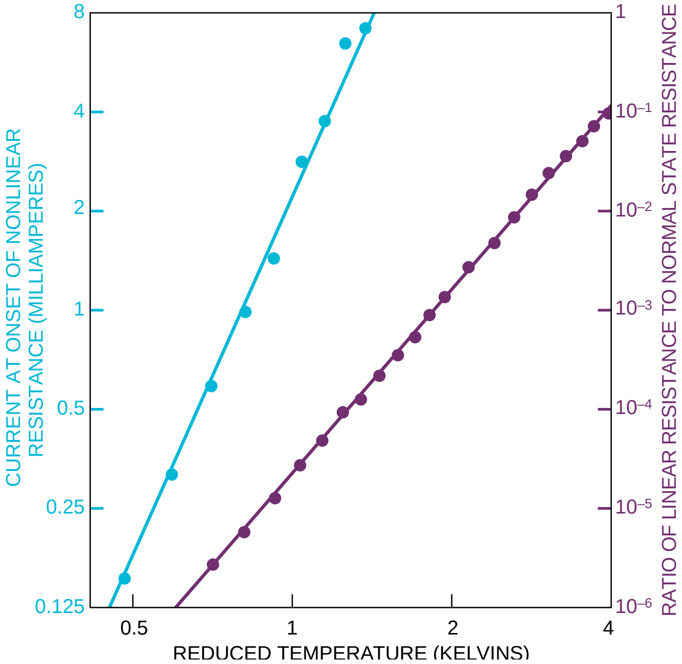


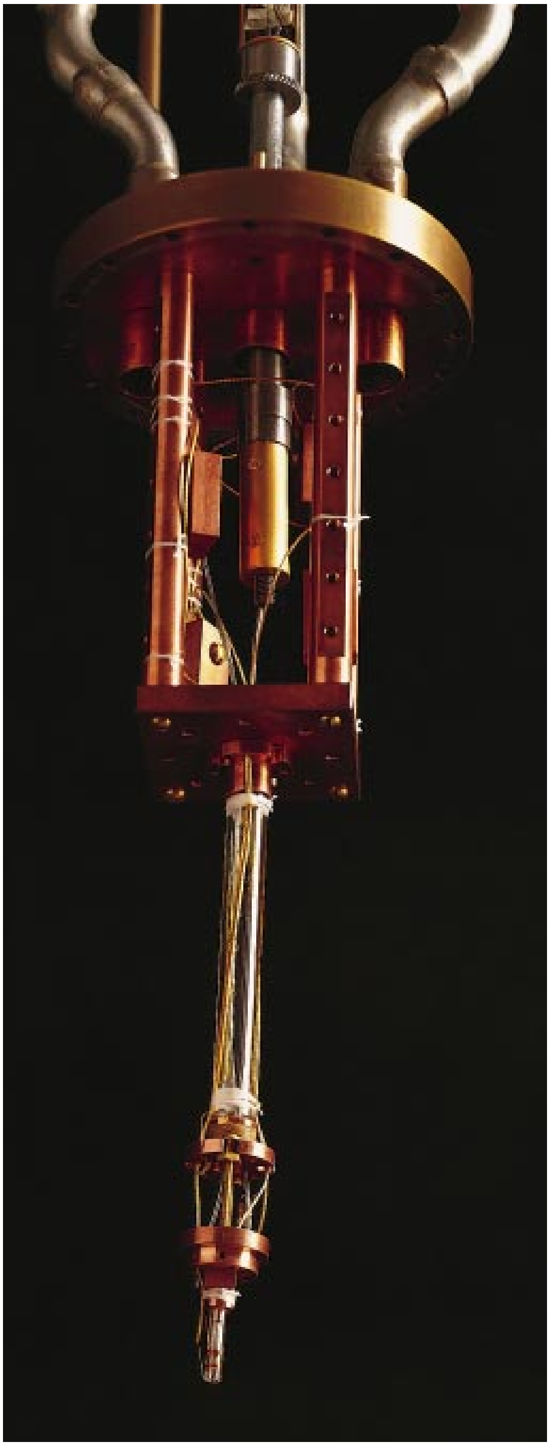
VORTEX GLASS

The SQUID Picovoltmeter

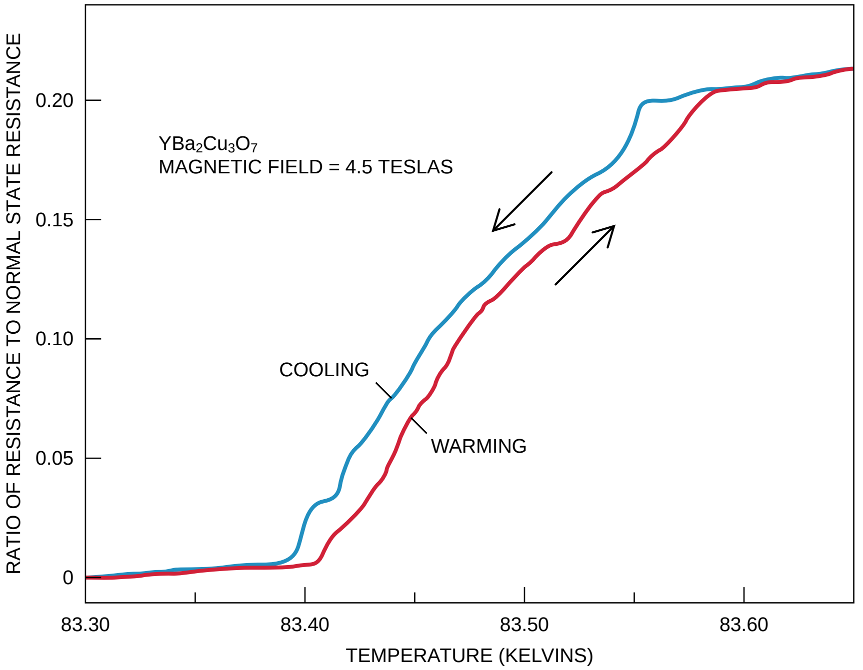
The device probes the different vortex states. The diagram (*top left*) shows the essential features of the picovoltmeter. The conventional superconducting and field-compensation coils apply to the sample a field of up to seven teslas. The isothermal can keeps the temperature of the sample to within a few millikelvins. Low-resistance wires running through a glass tube connect the sample to the SQUID, which measures minute electrical changes. In the photograph (*right*) the magnetic coils and the vacuum and isothermal cans have been removed for clarity. Measurements conducted with the device have confirmed the vortex glass model. One experiment, the results of which are displayed (*bottom left*), looked at the current (*blue*) and resistance (*purple*) in a region where the electrical properties of the sample are nonlinear. The data lie in a straight line, as predicted by theory. The reduced temperature is the difference between the temperature of the sample and that where the superconducting vortex glass phase first occurs.







ductors envisioned for technological use must inevitably be dirty. In fact, researchers working with conventional superconductors carefully engineer such defects into the material. Generally, the dirtier a superconductor is, the more current it can carry. Such imperfections are desirable because they "pin" vortices and prevent them from moving in response to the Magnus force. Vortex lines prefer to sit at pinning sites in the crystal lattice because in doing so they lower their energy. The situation is analogous to that of a marble rolling around on top of a table that contains a few small holes. Common experience tells us that the marble prefers to sit in one of the holes in the table, where its gravitational potential energy is lowest.



COOLING AND HEATING of a very clean crystal of the superconductor YBCO in a magnetic field produce resistance plots that do not exactly retrace one another. The measurement shows that the vortex lattice melts abruptly. In effect, the vortex liquid can be slightly "supercooled" before it freezes, much as pure water can.

Pinning has a characteristic effect on the vortex solid in a superconductor: it disrupts the regular lattice pattern that would otherwise form in an ideal, pure material. In other words, the pinning prevents the material from condensing into a perfect vortex solid in strong magnetic fields. The phase that forms instead is what researchers now describe as a vortex glass. The term is appropriate because the positions of the vortices form an irregular, disordered pattern, similar to that assumed by molecules in glass.

The vortex glass idea was not widely accepted when it was first proposed in 1989. Other descriptions, such as those that treat the vortex lines as individual particles, could also account for the observed behavior of the high-temperature materials. The vortex glass model, however, made several testable predictions. It postulated that, given a sufficiently large concentration of pinning defects, the vortex liquid would freeze smoothly into a glass. This behavior contrasts with that shown for pure materials, in which the vortex liquid solidifies rather abruptly and in a hysteretic manner. The vortex glass model also described the behavior of the resistivity as a function of temperature, current and magnetic field.

A clear verification of the vortex glass model came about only when researchers could carry out extremely sensitive transport measurements of a type not usually done in superconductors. Specifically, experimenters designed an apparatus that could measure the voltage across a high-temperature superconductor with subpicovolt (10^{-12} volt) resolution—an accuracy previously unavailable. The picovoltmeter used a superconducting quantum interference device, or SQUID. Such devices rely on quantum effects to measure minute current and voltage changes. With a SQUID, the picovoltmeter had a sensitivity about one million times greater than that of an ordinary voltmeter. The resolution was sufficiently high to confirm or dispute the vortex glass theory.

The principles behind the picovoltmeter itself are rather simple. Samples are placed in an insulating container that can maintain the temperature inside to within a few millikelvins. Superconducting coils surround the container and apply a uniform magnetic field to the sample. Current is sent through wires connected to the sample, and the SQUID then measures the resistance of the sample. The SQUID and superconducting magnets are conventional, low-temperature superconductors—an example of the old technology helping us to measure and grasp the new.

The apparatus resoundingly confirmed the predictions of the vortex glass model. The measured resistances and currents matched those predicted by the model, smoothly going to zero as the temperature was reduced to the freezing point of the liquid [*see box on opposite page*]. This smooth behavior is very different from that found for very clean crystals: in them, the phase transition is sudden and hysteretic. The observation shows the importance of pinning-induced disorder—the role of "dirt," so to speak—in changing the dynamics of the melting transition. Instead of a solid, the vortex liquid in the disordered crystal freezes into a vortex glass.

The high-temperature superconductors have proved to be a wonderful testing ground for our knowledge of type II superconductivity. For instance, we can now conclude that the vortex glass also exists in conventional superconductors, although the state may be hard to see. Nevertheless, it remains to be seen whether the knowledge can be translated effectively into applications. Researchers are actively looking for the kind of defects that could pin vortices most effectively. Much has been accomplished to fashion superconducting wires and to improve their current-carrying capability. Our present microscopic understanding of the various vortex states can only help us engineer better materials for the applications we all so eagerly await.

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