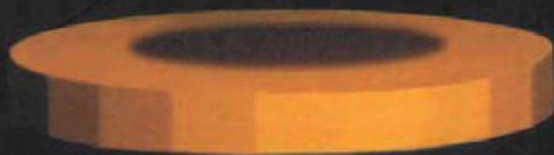


Superc nductivity



R e v i s e d E d i t i o n

V. L. Ginzburg · E. A. Andryushin



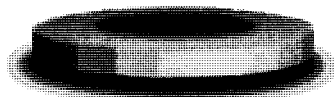
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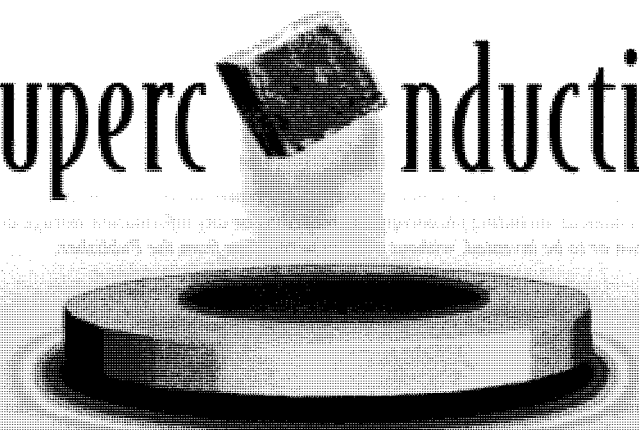
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Superconductivity



Revised Edition

V L Ginzburg · E A Andryushin

P N Lebedev Physics Institute, Russia

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Revised Edition

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To the Reader

Superconductivity is a physical phenomenon which is customarily described without grudging epithets. Indeed, its nature had remained unclear for many years. To discover the mechanism of this phenomenon, several decades of efforts of many physicists were needed. But even now, after the discovery in 1986 and 1987 of the so-called high-temperature superconductors, superconductivity is still under a veil of mystery — some key questions have yet to be answered. But to approach them, we first have to trace the path traversed.

We shall tell you what superconductivity is, how it was discovered, what its main properties are, where superconductors are applied now and how they are most likely to be widely used in future.

We hope that our book will be the simplest of all popular books devoted to superconductivity in the recent past. At the same time, however, it will be less detailed and the least precise. The reader should not be surprised if in more extensive books, he comes across statements in more precise formulations than those given in our book. We have not always indicated the necessity of such a specification lest the text be overloaded with footnotes and digressions.

This book is organized by the canon of increasing complication, from the first discovery over eighty years ago through many years of studies to the latest sensations. The reader may choose topics according to his interests. To have an idea of superconductivity, it suffices to read the chapter on its discovery, and after that one can read

chapters on its applications and those describing the superconducting boom. The chapters “Physics of Superconductivity” and “The Nature of Superconductivity” will be useful for those who take an interest in physics, which is our greatest desire.

.....

Preface to the Revised Edition

Several years after the discovery of High- T_c superconductors (HTS) in 1986–87, there was an expectation of a boom in superconductivity. This small book was first written in 1989. It was the time when much enthusiasm was seen in the discovery of HTS. Now, in 2004, it is clear that the hopes raised for the widespread usage of HTS technology may have been over-inflated.

But superconductivity applications are nevertheless enormous, more so for the *usual* Low- T_c superconductors than for the new High- T_c ones. Let us name the Low- T_c superconductors as LTS, and the High- T_c superconductors as HTS; such abbreviations are generally recognizable.

This book is aimed at readers with an interest in physics and driven by a curiosity to learn more about nature. The understanding of the mechanism and processes in HTS is the focus of attention. To understand what occurs in HTS (as we did earlier for LTS) and then to try and create a substance which is superconducting at room temperature is one of the grand missions of solid state physicists. As before, we can name Room- T_c superconductors as RTS. But now RTS seems to be only a dream. However, let us not forget that HTS was also only a dream before 1986. Science needs new people to make dreams come true — so it makes great sense in having a new edition. Although the changes in this new edition are minor, let us hope it will be useful to the aspiring readers.

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Chapter 1

The Discovery of Superconductivity

The Beginning

In 1911 a Dutch physicist, H. Kamerlingh-Onnes, discovered the phenomenon of superconductivity. He measured the electric resistance of mercury at very low temperatures. Onnes wanted to know how small the resistance to an electric current can become if a substance is purified and the temperature (*thermal noise*) is lowered as much as possible.

The result of this investigation was unexpected: at a temperature below 4.15 K,^a the resistance disappeared almost instantaneously. The behavior of resistance as a function of temperature is shown schematically in Fig. 1.

An electric current is the motion of charged particles. At that time it was already known that electric current in a solid is a flux of electrons. Electrons are negatively charged and are much lighter than the atoms that make up any substance.

Each atom, in turn, consists of a positively charged nucleus and electrons which interact with the nucleus and among themselves in

^aDegrees on this scale are conventionally denoted by the letter K. One degree Kelvin is equal to the Celsius degree, but the Kelvin scale is counted from absolute zero. On the Celsius temperature scale, absolute zero is equal to -273.16°C . The abovementioned temperature of 4.15 K is therefore equal to -269.01°C . Further on, we will use rounded-off values.

accordance with Coulomb's law. Each atomic electron occupies a certain *orbit*. The nearer the orbit is to the nucleus, the stronger the electron is attracted by it and therefore the greater is the energy needed to detach such an electron from the nucleus. The outermost electrons are, in contrast, readily detachable, although some energy is needed for this process too.

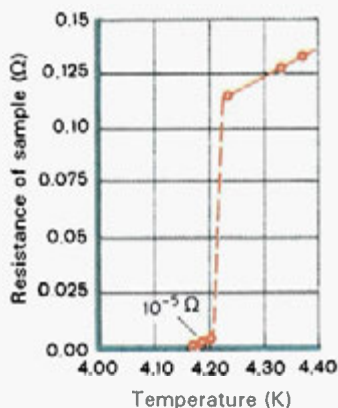
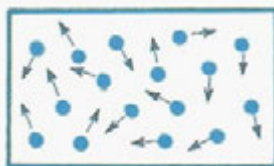


Fig. 1. Data from one of Onnes' pioneering works devoted to superconductivity. According to current data, the curve should now be shifted by 0.05 K, since the temperature scale used by Onnes was inaccurate.

Outermost electrons are called valence electrons. They are actually detached from the atoms when the latter unite to make up a solid, and form a gas of almost-free electrons. This is a simple, beautiful, and typically correct physical picture: a portion of a substance can be thought of as a vessel filled with an *electron gas* (see Fig. 2).



Generation of an electric field by a voltage applied to a sample gives rise to a wind in the electron gas, which occurs due to the difference of pressures. This wind is just an electric current.

Metals

One knows that not all substances conduct electric current. In a *dielectric*, valence electrons remain “tied” to their atoms, and it is not so easy to make them travel across a sample.

It is rather difficult to explain why some substances turn out to be metals while others are dielectrics. This depends on the atoms they are composed of and also the arrangement of these atoms. Conversion is sometimes possible when the positions of atoms change. Under pressure, for example, atoms can get close enough to each other for a dielectric to become a metal.

Dielectrics do not conduct current, but in metals the electrons do not move quite freely either. They collide with atomic “skeletons” from which they have “detached”, and are scattered by them. This produces friction or, as we usually say, an electric current encounters *resistance*.^b

In a superconducting state, the resistance dies out and becomes zero, i.e. the electrons move without friction. At the same time, we know from our everyday experience that such motion seems to be impossible.

Physicists have made efforts to settle this contradiction for dozens of years. The discovered property is so unusual that metals possessing resistance are called *normal*, as opposed to *superconductors*.

Resistance

The electric resistance R of a piece of metal is measured in Ohms and is determined by the size and material of the sample. In the formula

^bThe occurrence of resistance is of course a much more intricate process and we shall dwell on it below.

$$R = \frac{\rho \cdot l}{S},$$

R is the resistance of the sample, S the sample cross-sectional area, and l the length (the sample size in the direction of current flow). Writing this formula, we go on comparing an electron with a gas — the wider and shorter the tube, the easier it is to blow a gas through it. The quantity ρ is the resistivity which characterizes the properties of the material which the sample is made of. Table 1 shows the resistivities of several substances at room temperature.

Table 1. Resistivities of several substances at room temperature.

Substance	Resistivity ρ (Ohm · cm)
Aluminium	2.8×10^{-6}
Lead	21.1×10^{-6}
Mercury	95.8×10^{-6}
*Asbestos	2.0×10^5
Rubber	4.0×10^{13}
Amber	1.0×10^{18}

*We present for comparison the room-temperature resistivities of several dielectrics.

Pure copper at room temperature has $\rho = 1.75 \times 10^{-6}$ Ohm · cm. Copper is one of the best and most widely-used conducting metals. Some other metals at room temperature are worse conductors.

As the temperature T is decreased, the copper resistivity gradually lowers, and at a temperature of several degrees K, it is 10^{-9} Ohm · cm, but it does not become a superconductor, whereas aluminium, lead and mercury pass over to a superconducting state. Experiments carried out with these substances show that the resistivity of a superconductor never exceeds 10^{-23} Ohm · cm, which is a hundred trillion times less than that of copper!

Residual Resistivity

The resistivity of a metal is temperature-dependent. The dependence $\rho(T)$ is shown schematically in Fig. 3. As the temperature rises, the resistivity increases and the vibrations of the atomic “skeletons” constituting the metal become stronger, making them a greater obstacle for the electric current. ρ_0 is a residual resistivity to which the sample resistivity “tends” if the temperature approaches absolute zero.

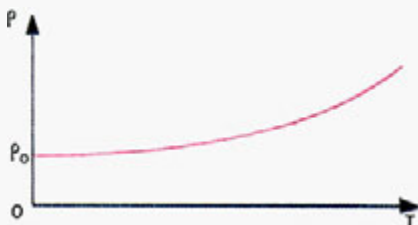


Fig. 3. Resistivity ρ of a metal as a function of temperature T .

Residual resistivity depends on the degree of perfection and composition of the sample. Any substance contains alien atoms — impurities as well as various other defects. The fewer the defects in a sample, the lower is its residual resistivity. It is precisely this dependence that Onnes was concerned with in 1911. Far from seeking “superconductivity”, he was just trying to find out how small the residual resistivity could be made by way of sample purification. He carried out experiments with mercury because at that time, mercury could be purified^c better than platinum, gold or copper (these metals are better conductors than mercury and Onnes had examined them before superconductivity was discovered; they are not superconducting).

Critical Temperature

As temperature is lowered, superconductivity sets in with a jump.

^cUsing a technique similar to water distillation.

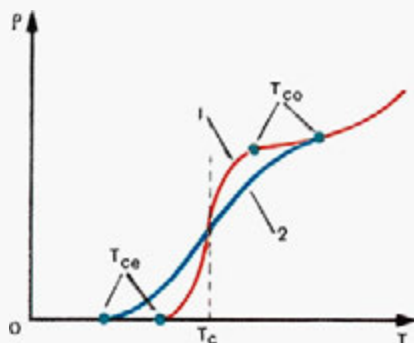


Fig. 4. Schematics of a superconducting transition showing the temperature dependence of resistance for sample 1 ("pure") and sample 2 ("dirty"). The critical temperature T_c indicates the middle of the transition, at which the resistance is half that in the normal state. T_{co} is the beginning and T_{ce} the end of the resistance fall.

The temperature T_c at which the jump is observed is called the *critical temperature*. A thorough analysis shows that such a transition occurs at a certain temperature range (see Fig. 4). The friction of moving electrons disappears irrespective of sample "purity", but the more uniform and perfect the sample, the sharper is the resistance jump, the jump width in the "most ideal" samples being less than one hundredth of a degree. Such samples are thought to be "good" samples or "good" superconductors, while in the "bad" ones, the jump width can reach tens of degrees. (This refers, of course, to the newly discovered superconductors for which T_c is large, up to a hundred degrees.)

Each substance has its own critical temperature. This temperature and the year of discovery of the corresponding superconductivity (more precisely, the first report on it) are indicated in Table 2 for several pure elements. Niobium has the highest critical temperature of all the chemical elements, but it does not exceed 10 K.

It was Onnes who not only discovered the superconductivity of mercury, tin and lead but was also the first to find superconducting

Table 2. Critical temperature T_c and the year of discovery of the corresponding superconductivity for several elements.

Element	Critical Temperature T_c (K)	Year of Discovery
Mercury	4.15	1911
Tin	3.69	1913
Lead	7.26	1913
Tantalum	4.38	1928
Niobium	9.2	1930
Aluminium	1.19	1933
Vanadium	4.3	1934

(mercury-gold and mercury-tin) alloys. Such attempts have continued since then and more new compounds have been tested for superconductivity, thus widening the class of superconductors.

Low Temperatures

The study of superconductivity made fairly slow progress. To observe the phenomenon, one has to cool metals down to very low temperatures, which is not a simple task. To fulfill such a task a sample must be placed in a cooling liquid. All the liquids known to us from our everyday experience freeze and solidify at low temperatures. It is therefore necessary to liquefy those substances which are gases at room temperature. Table 3 shows the boiling (T_b) and melting (T_m) temperatures of five substances (under atmospheric pressure).

If we lower the temperature of a substance below T_b , it liquefies, and below T_m , it solidifies. (Helium remains a liquid up to absolute zero under atmospheric pressure.) So, for our purpose, some of the substances indicated can be used in the interval between T_b and T_m . Till 1986, the maximum known critical temperature of superconductivity hardly exceeded 20 K, and that is why studies of superconductivity could not be carried out without liquid helium. Nitrogen is

Table 3. Boiling and melting temperatures of several substances at a normal pressure.

Substance	Boiling Temperature T_b (K)	Melting Temperature T_m (K)
Helium	4.2	—
Hydrogen	20.3	14.0
Neon	27.2	24.5
Nitrogen	77.4	63.3
Oxygen	90.2	54.7

also widely used as a coolant. Nitrogen and helium are employed in successive stages of cooling. They are both neutral and harmless.

The liquefaction of helium is itself a very interesting and fascinating problem which was the focus of attention for many physicists between the 19th and the 20th centuries. Onnes attained it in 1908. For this purpose, he set up a special laboratory in Leiden in the Netherlands. For 15 years, the laboratory had the monopoly of unique research in the new temperature range. In 1923–1925, liquid helium was obtained in two other laboratories, in Berlin and Toronto. In the Soviet Union, the appropriate equipment was constructed in the early 1930s in the Kharkov Physical Engineering Institute.

After the Second World War, a whole branch of industry appeared and gradually developed in many countries laboratories that supplied liquid helium. Before that, all the research laboratories had to make their own liquid helium. The technical difficulties and physical complexity of the phenomenon hampered the accumulation of knowledge in the field of superconductivity. It was twenty-two years after the first discovery that the second fundamental property of superconductors was revealed.

The Meissner Effect

This effect was reported in 1933 by two German physicists, W. Meissner and R. Ochsenfeld. Superconductivity had hitherto been thought of as merely a disappearance of electric resistance. But it is a more sophisticated phenomenon than simply the absence of resistance. Superconductivity is, in addition, a certain reaction to an external magnetic field. The *Meissner effect* consists of forcing a constant, but not very strong, magnetic field out of a superconducting sample. The magnetic field in a superconductor is weakened to zero, superconductivity and magnetism being, so to speak, “opposing” properties.

When seeking new superconductors, one has to test a material for both these principal properties: whether the resistance vanishes and whether the *magnetic field* is forced out. In “dirty” superconductors, the fall of resistance with temperature may sometimes be much more extended than is shown in Fig. 1 for mercury (see also Fig. 4).

In the history of these studies, physicists frequently mistook some other fall of resistance for superconductivity, even a fall due to a common short circuit. To prove the existence of superconductivity, it is necessary, at least, that both principal properties be observed. A rather showy experiment demonstrating the Meissner effect is illustrated in Photo 1: a permanent magnet hovers over a superconducting cup. Such an experiment was first carried out by a Russian physicist, V. K. Arkadyev, in 1945.

In a superconductor, there exist currents that force out the magnetic field; the magnetic field of these currents repels the permanent magnet and compensates for its weight. The walls of the cup also play an essential role: they repel the magnet toward the center. The position of the magnet over the flat bottom is unstable. Driven by accidental kicks, it will move aside. Such a floating magnet reminds one of the legends about levitation. The most well-known of these legends is that of a religious prophet’s coffin. The coffin was left in a cave where it hovered in the air without any visible support. One cannot say for sure

now whether such stories are not based on realistic phenomena. It is now technically feasible to “realize the legend” on the basis of the Meissner effect.

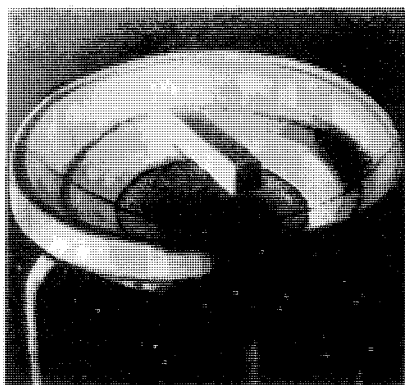


Photo 1. A permanent magnet several centimetres long floats above the bottom of a superconducting cup. The cup stands on three copper legs which are immersed in liquid helium, and the cup itself is embraced by helium vapour to maintain the superconducting state.

Magnetic Field

Modern physics employs the concept of a field to describe the action at a distance of one body on another without contact. For example, charges and currents interact by means of an electromagnetic field. All those who have studied the laws of electromagnetic field know the visualisation of the field — the picture of lines of force (field lines). This image was first utilized by an English physicist, M. Faraday. As an illustration, it would be instructive to recall another image of the field employed by another English physicist, J. C. Maxwell.

Imagine a field as a moving liquid, for instance water flowing along the direction of the lines of force. Using this, we can describe, say, the Coulomb interaction between two charges as follows. Suppose there is a basin which is (for simplicity) flat and shallow, whose top view

is presented in Fig. 5. Let there be two holes in the bottom; one for water inflow (we think of it as a positive charge), the other for efflux (which is a discharge or a negative charge). The water flowing in such a basin is analogous to an electric field between two fixed charges. Water is transparent and its flow invisible, but if in the jets we immerse a "trial positive charge" — a ball hanging by a thread — we immediately feel a force: the ball is being taken away by the liquid.

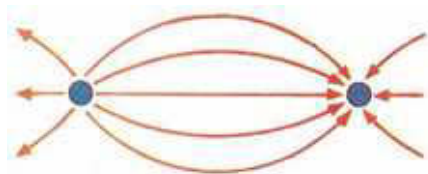


Fig. 5. The field lines, lines with arrows, are shown as if they were water jets.

The water carries the ball away from the source, which illustrates the repulsion of like charges. The ball is attracted to the drain, or a charge of opposite sign, the attractive force between the charges depending on the distance between them, as is prescribed by Coulomb's law.

Currents and Fields in Superconductors

To describe the behavior of currents and fields in superconductors, one should recall Faraday's law of induction. For our purpose, it is useful to give a more general formulation of this law than what we know from any school course. The law of magnetic induction describes generally the relationship between electric and magnetic fields. If an electromagnetic field is compared to a liquid, then the interaction of the electric and magnetic components of the field can be compared to an interaction between the quiet (laminar) and the eddy (vortex-type) flows of the liquid. Each of these flows can exist by itself. Suppose we are dealing, for example, with a quiet, wide flow — a homogeneous electric field. If we try to change this field, i.e. slow down or speed up

the liquid flow, we inevitably induce vortices — a magnetic field. A change in the magnetic field necessarily entails the appearance of an electric field. The latter, in turn, generates current in the circuit, and thus we have the ordinary magnetic induction: magnetic field variations induce current. This is just the physical law that works in all the electric power stations of the world — one way or another, variations in the magnetic field in a conductor are induced. The induced electric field generates the current that comes to our homes and industries.

But let us return to superconductors. For the existence of a constant current in a superconductor, an electric field is not needed, and in an equilibrium situation, the electric field in a superconductor is equal to zero. Such a field would accelerate electrons, and in superconductors, there is no resistance, i.e. friction that would counterbalance the acceleration. An arbitrarily small constant electric field would cause an infinite increase in current, which is impossible. An electric field occurs only in the nonsuperconducting parts of the circuit. In superconductors, the current exhibits no voltage drop.

Speculations suggest no obstructions to the existence of a magnetic field in a superconductor. But clearly, a superconductor does hamper magnetic field *variations*. Indeed, a change in the magnetic field would induce current which would generate a magnetic field compensating for the initial change.

So, any superconducting circuit must retain the magnetic field flux flowing through it. (The *magnetic flux* through a circuit is simply the product of the magnetic field strength and the circuit area.)

The same must take place in the bulk superconductor. If, for example, a magnet is brought near a superconducting sample, we shall see that its magnetic field cannot penetrate inside. Any such “attempt” causes the occurrence of a current in the superconductor whose magnetic field compensates for the external field. As a result, the magnetic field is absent from the bulk superconductor, and along the surface, the current flows exactly as required for this purpose. In the bulk of a conventional conductor immersed in a magnetic field, everything happens in exactly the same way. However, in the presence

of a resistance, the induced magnetic field attenuates rather rapidly, and, due to friction, its energy is converted into heat. (This heat can be readily revealed in experiments. You will feel it if you bring your hand near an operating transformer.) In a superconductor, since there is no resistance, the current does not attenuate and does not let in the magnetic field for an arbitrarily long time. The picture we have described is exact and has been repeatedly confirmed in experiments.

We shall now consider another speculative experiment. We shall take the same piece of a superconducting substance but at a sufficiently high temperature that the substance is still in a normal state. We insert it into a magnetic field and wait till everything settles — the currents are attenuated, the substance is pierced by a magnetic flux. Now we start lowering the temperature and wait for the substance to become superconducting. It seems that the temperature decrease must in no way affect the magnetic field picture. A magnetic flux in a superconductor must not change. If we now remove the external magnetic field, the superconductor must oppose this change, and the superconducting currents maintaining the magnetic field inside must flow on the surface.

However, such behavior does not correspond at all to what we observe in practice: the Meissner effect occurs in this case too. If a normal metal in a magnetic field is cooled, in the course of transition into the superconducting state, the magnetic field is in fact forced out of the superconductor, and on its surface there exists a persistent current providing for zero field in the bulk superconductor. This picture of a superconducting state is always observed irrespective of the way in which transition into this state is realized.

This description is of course an idealization, and, in the course of our narration, we shall make it increasingly complicated. It is, however, worth mentioning that there are two types of superconductors which react differently to the magnetic field. We begin by describing the properties of *type I superconductors* whose discovery marked the dawn of the era of superconductivity. Later, *type II superconductors* were discovered with somewhat different properties. It is mainly these superconductors that find practical applications.

Ideal Diamagnetism

The action of forcing out a magnetic field is to a physicist as surprising as the absence of resistance. The point is that a constant magnetic field customarily penetrates everywhere. A grounded metal screening an electric field is by no means an obstruction to a magnetic flux. For a magnetic field, the boundary of a body is in most cases not a wall that would obstruct its “flow”, but merely a small step at the bottom of the pool altering the depth and thus slightly affecting this “flow”. The magnetic field strength in a substance changes by a fraction of a hundredth or even thousandth of a percent as compared to its strength outside the substance (except for magnetic substances such as iron and other ferromagnets, where a strong internal magnetic field is added to the external one). In all other substances, the magnetic field is either slightly strengthened (such substances are called *paramagnets*) or slightly weakened (in substances called *diamagnets*).

In superconductors, the magnetic field is weakened to zero and they are therefore *ideal diamagnets*.

A screen of permanently maintained currents alone can “obstruct” a magnetic flux. A superconductor itself creates such a screen on its surface and maintains it for an arbitrarily long time. That is why the Meissner effect, or the ideal diamagnetism of a superconductor, is no less surprising than its ideal conductivity.

Some Facts from History

In the next chapter, we shall discuss the remarkable properties of superconductors in more detail, and we conclude here with an enumeration of the most important works done by physicists in the course of studies of superconductivity.

These are, first of all, the abovementioned discoveries of H. Kamerlingh-Onnes (1911) and W. Meissner and R. Ochsenfeld (1933). The first theoretical explanation of the behavior of a superconductor in a magnetic field was given in England (1935) by two German emigrant physicists, F. London and H. London.

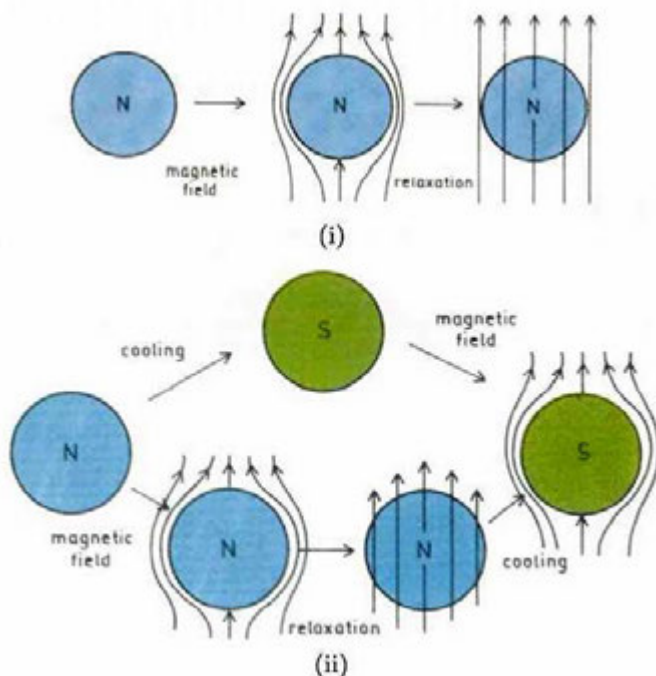


Fig. 6. What happens to a metal ball upon application of a magnetic field?

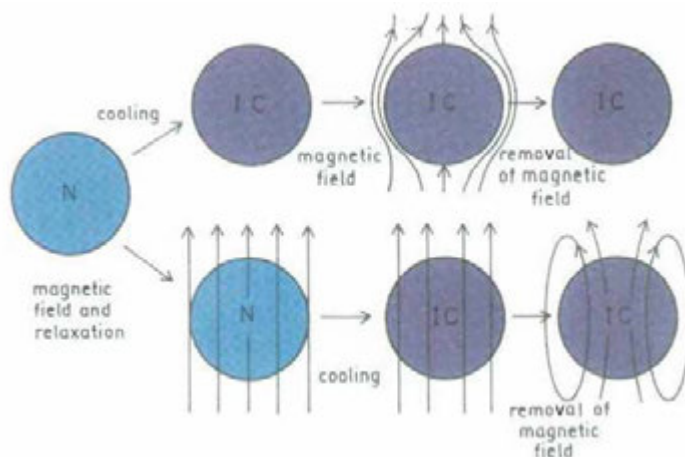
Magnetic field lines are shown with arrows piercing or flowing round the sample. The state of the ball is denoted by the letters N — normal metal, S — superconductor, and by IC we denote a hypothetical state, the “ideal conductor” — a metal that shows neither resistance nor the Meissner effect.

Three types of behavior are shown:

(i) A normal conductor possessing a finite resistance at any temperature. When this conductor is immersed in the magnetic field, currents arise that resist the field’s penetration into the metal, according to the laws of electromagnetic induction. But since the resistance is nonzero, these currents decay rapidly and the field penetrates into the ball.

(ii) Now consider a transition to a superconducting state by two routes. In the first we lower the temperature below T_c , causing the transition to occur, then apply a magnetic field which is forced out of the sample (S). In the second we begin by applying the field, which penetrates the sample (N), then lower the temperature below T_c , causing the field to be forced out.

(iii) In our hypothetical ideal conductor which does not exhibit the Meissner effect, we would see quite different behavior. If the temperature is lowered in the presence of the field, then when the resistanceless state is achieved the magnetic field is conserved, and even confined if the external field is removed. Such a magnet could only be demagnetised by raising the temperature again. However, such a state has never been observed in experiments.



(iii)

Fig. 6. (*Continued*)

In 1950, L. D. Landau and one of the authors of this book (VLG) wrote a paper suggesting a more general theory of superconductivity. This description proved to be convenient and is used to the present day.

The mechanism of the phenomenon was discovered in 1957 by three American physicists, J. Bardeen, L. Cooper and J. R. Schrieffer. The theory is called BCS (the abbreviation is derived from the first letters of their names), and the mechanism itself (which implies electron pairing) is often called *Cooper pairing* since the idea was suggested by L. Cooper. An important contribution to the development of the concepts of BCS theory was made by Soviet physicist L. P. Gor'kov, who demonstrated the relationship between BCS theory and preceding concepts of superconductivity.

Besides that, in the 1950s, great influence was exerted by the discovery and study of compounds with comparatively high critical temperatures and which are capable of withstanding very strong magnetic fields and conducting high current densities in a superconducting state. The culmination of these studies was, perhaps, the experiment

performed by J. Kunzler and his collaborators (1960). They demonstrated that at $T = 4.2$ K, a Nb_3Sn wire in a field of 80,000 Oe (they simply had no stronger field at their disposal) conducts current with a density of 100 kA/cm^2 . The superconductors discovered at that time are still operating in technical devices. Such materials are now referred to as a special type of superconductors called *hard superconductors*.

In 1962, an English physicist B. Josephson predicted theoretically some unusual phenomena that occurred on superconductor contacts. These predictions were then fully confirmed and the phenomenon itself was called *weak superconductivity* or the Josephson effect, and soon found practical applications.

Finally, the 1986 paper of two physicists, Swiss K. A. Müller and German G. Bednorz, who worked in Zürich, marked the discovery of new classes of the so-called high-temperature superconducting substances (HTS). It resulted in an avalanche of new research activities in this field which will affect the lives of mankind in the near future. A new technological revolution had begun.

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Chapter 2

Physics of Superconductivity

How to verify that the Resistance of a Superconductor is Actually Zero?

One can readily draw a graph (see Figs. 1 and 4) “resting” on a curve against the abscissa axis, but it is much more difficult to make sure that the resistance is not merely very low, but actually zero. When measuring resistance, a physicist uses a device sensitive enough to register the expected value. If the measured quantity suddenly decreases 10 or even 100 times, the pointer stops deflecting. It is precisely due to this fact that the temperature dependence of the resistance, first obtained by Onnes, looked so uneven. He needed nearly a year to make certain that the resistance of a superconducting substance was lower than one that could be registered by the most sensitive device of that time. This, however, does not prove that the resistance is strictly zero, but such a rigorous experimental proof is inaccessible. A physical quantity may be assumed equal to zero if its possible deviation from the theoretically calculated “zero” is so small that it cannot be recorded by any measurement.

Onnes conducted the following experiment. Into a vessel with liquid helium, which served as a cooler, he immersed a superconducting ring with a current circulating in it (see Fig. 7). If the ring had a resistance other than zero, the current in the ring would decrease and the magnetic field that created such a current would change. The