INTRODUCTION

This tutorial is based on a course of lectures on "Superconductivity," that the author delivered over the years for senior students of the Institute of Physics, Nanotechnology and Telecommunications (IFNIT) in St.Petersburg Polytechnic University.

The increased interest to the physics of superconductivity in recent years is due to the opening in 1986 high-temperature superconductors, which on the one hand made it possible to use for cooling of the superconducting transition not expensive liquid helium, but cheap liquid nitrogen, while on the other hand, raised hopes to obtain superconductivity at room temperature.

Experimental and theoretical studies of physics of superconductivity not only have laid the foundation for creating superconductors with the necessary technical properties but also have leaded to a better understanding of the different branches of physics. These studies opened a number of phenomena, not directly associated with the loss of resistance, such as the Meissner and Josephson effects, Shapiro steps, magnetic flux quantization, macroscopic coherence of the wave functions, etc. They have given new physical images and concepts: Cooper pairs, Abrikosov vortices, intermediate state, Shubnikov phase.

When creating this course the author have aimed to introduce future physicists to these original ideas and images that have enriched not only the solid state physics, but all fundamental physics.

All presentation is conducted using the International System of Units (SI). In some graphs, taken from the original works, there are also the units used in electromagnetism CGS, in particular Gauss and Oersted. Their transfer in the SI is based on the ratio of 1 G =10-4 Tl; 1 Oe=80A / m. It should be borne in mind that most of the formulas in the CGS system has a different appearance.

CHAPTER 1. SOME BASIC FACTS

§1.1. The absence of electrical resistance

In 1908, the Dutch physicist Heike Kamerlingh Onnes managed to liquefy the last inert gas - helium. This opened him the opportunity to study the properties of materials at temperatures near absolute zero. The most interesting results were obtained in the study of the electrical resistance.

At that time in comprehension of the mechanism of conductivity there were many gaps. However, it was known that the charge transfer is caused by the movement of electrons. The temperature dependences of the electrical resistance of many metals were measured. It was found that at room temperatures, the resistance is directly proportional to temperature. It was also possible to come to a conclusion that at lower temperatures the resistance falls more slowly. In principle, one could assume three possible options:

1. When the temperature decreases the resistance gradually decreases to zero (Figure 1.1, curve 1).

2. Resistance tends to some finite value (Figure 1.1, curve 2).

3. Resistance passes through a minimum, and at very low temperatures becomes infinite. (Figure 1.1, curve 3).

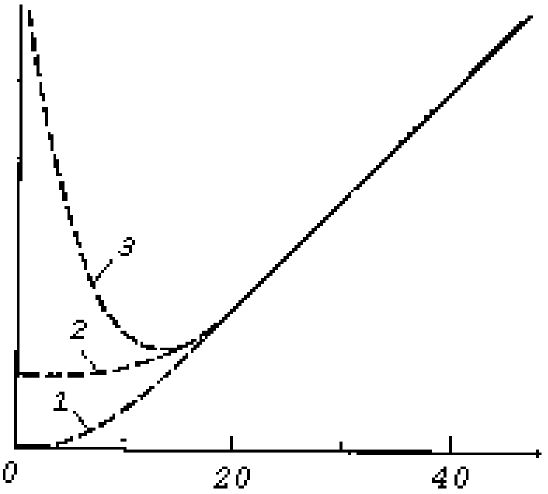

Fig. 1.1. The temperature dependence of the electrical resistance

The first option based on the experimentally observed rapid decrease in resistance with cooling. The third option corresponds to the notion that at low temperatures, all electrons should have a foothold near their atoms and cease to be free. The second variant was confirmed by Onnes experiments with different samples of platinum and gold (Fig.1.2), these metals at the time were in a sufficiently pure form. When the temperature approaches absolute zero the resistance aspired to the so-called residual value, depended on the purity of the sample. Onnes concluded that platinum and gold in pure form at temperatures close to absolute zero, should have negligibly small resistance.

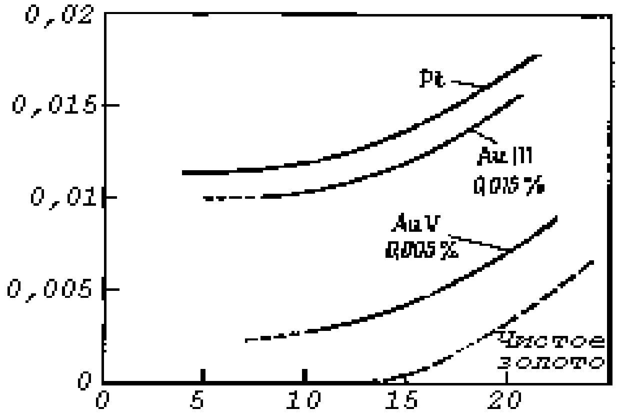

Fig. 1.2. The electrical resistance of various metals

However, in 1911 when experimenting with mercury (it can be obtained in a more pure form), he found that the observed effect has nothing to do with a gradual decrease in resistance with temperature - the change was abrupt (Figure 1.3). Onnes himself pointed out that the mercury moved to a new state and named it superconducting. The significance attached to this discovery, is evidenced by the fact that in 1913 Kamerlingh Onnes was awarded the Nobel Prize in Physics.

Looking at Figure 1.3 brings forth a natural question: what is the value of the jump of resistance, in other words, to what extent it is correct to speak about the disappearance of electrical resistance?

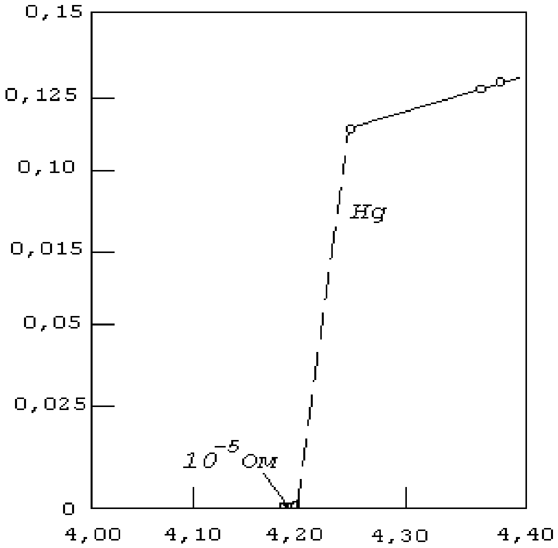

Fig. 1.3. The superconductivity of mercury

To answer this question it was necessary to find a sufficiently accurate method of measuring the resistance. In the first experiments, measurements were made on the basis of Ohm's law. Thus it was possible to install only the fact that the resistance decreases abruptly at more than one thousand times, and becomes lower than the detection limit. Already in 1914 Onnes used more precise method to measure extremely low resistance values. He measured the attenuation of the current in a superconducting ring. If the resistance exists, due to the Joule losses current should decrease with time.

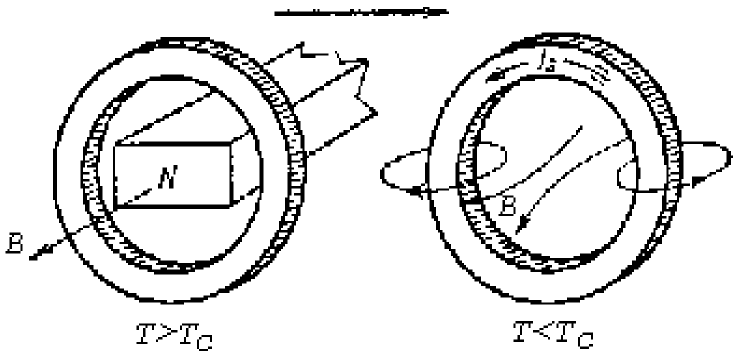

Fig. 1.4. The emergence of the persistent current in a superconducting ring.

The principle of the method is shown in Figure 1.4. Suppose that a ring of superconducting material (for example, lead) is in the normal state, i.e. it has a temperature above the transition temperature T_c. The magnet creates magnetic field in a ring. Then the ring is cooled to a temperature at which it becomes superconducting. The magnetic field is not affected. Now remove the magnet. According to the law of electromagnetic induction the induction current arises in the ring. The speed of its decay allows to find the magnitude of the resistance. Fall of current for 1% per 1 hour would correspond to a drop in the resistance during the transition to the superconducting state at 8 orders of magnitude. Nowadays, there are experiments with no change in the current during decades, which says that a drop in resistance is not less than 15 orders of magnitude. All these data allow us to legitimately assume that in the superconducting state, the electrical resistance really disappears.

Soon after the discovery of superconductivity in mercury Onnes was able to show that other metals may become superconducting. The transition temperatures of them turned out to be very low - a few Kelvin. For decades, we were searching for materials with higher transition temperatures. It turned out that many of the metals and semiconductors and alloys have superconducting properties. However, the maximum found critical temperature was only 23 K - the alloy Nb_3Ge.

Immediately after the discovery of the phenomenon its theoretical studies began. The scientists proposed different mathematical approaches to calculate the distribution of currents, magnetic field configuration, etc. But microscopic theory explaining the nature of the phenomenon of superconductivity was created only 46 years after the discovery of the phenomenon. In 1957 American physicists Bardeen, Cooper and Schrieffer showed that at temperatures below the critical the conduction electrons are bound in pairs and explained the nature of this binding. Later we will discuss the general provisions of this theory - the so-called BCS theory, as well as consider other theoretical approaches existed before its creation and continuing to be useful at the moment.

After the creation of the BCS theory, when the physical processes responsible for superconductivity became clear, the experiments began in the creation of artificial materials with high transition temperature. The substances with a complex structure were proposed - consisting of planes, one-dimensional filament structure, etc. But all the investigations had no success, although the problem of high-temperature superconductivity, along with the creation of fusion reactors, considered the most important applied problems of modern physics.

And in 1986, when scientists have already begun to lose faith in the fact that high-temperature superconductivity can exist, there was an article by Bednorz and Muller about the discovery of superconductivity in a new class of materials - ceramics - at a temperature of 35 K! It was a breakthrough; the critical temperature has jumped 1.5 times after decades, when the promotion at 0.1 K was considered a great success. A rapid investigation of a new class of substances began. Every month, every week brought new results: 40 K, 60 K, 90 K, 100 K. Nowadays reliable record critical temperature is 135 K.

One may ask why this phenomenon is called high temperature superconductivity, when temperatures are minus 150 – 180 C. In any case, for the existence of superconductivity the materials have to be very much cooled. The important difference is that earlier the cooling to the desired temperature could be achieved only by using helium, as soon as it remained liquid in desired temperature range. Helium is very expensive and its amount in nature is not very large. At temperatures above 77 K, i.e. boiling point of nitrogen, the liquid nitrogen can be used for cooling, and in nature there is a lot of nitrogen (let's recall composition of the air), therefore it is very inexpensive.

We will mainly discuss issues concerning the ordinary (not high-temperature) superconductivity. The fact is that the theory of high-temperature superconductors (HTSC) is not yet established, due to the complexity of their crystal structure. Most phenomena observed in ordinary superconductors, occur in high-temperature superconductors, so that the differences relate only to the temperature values. Therefore, the analysis of these phenomena on the example of conventional superconductors allows to enter into the essence of problems and to understand the nature of the processes. HTSC and specific phenomena occurring in them will be discussed only in the last chapter of the book.

§1.2. Expelling the magnetic field from superconductors.

The magnetic properties of superconductors are as nontrivial as electric ones. In 1933, Meissner and Ochsenfeld found that the superconductor in a magnetic field behaves as a perfect diamagnetic, inside which the magnetic induction is zero. In other words, the magnetic field is expelled from the bulk superconductor. This is due to the appearance of the screening currents on the surface whose magnetic field completely compensate the external field throughout the volume of the sample. This phenomenon is called the Meissner effect.

At first glance it may seem that the perfect diamagnetism of superconductors is a consequence of zero resistance. Indeed, if we carry a sample in a magnetic field, as a result of electromagnetic induction, the induction currents arise. In normal metals they would decay with time because of Joule heating. In superconductors the resistance is zero and the currents do not decay with time and continue to further screening.

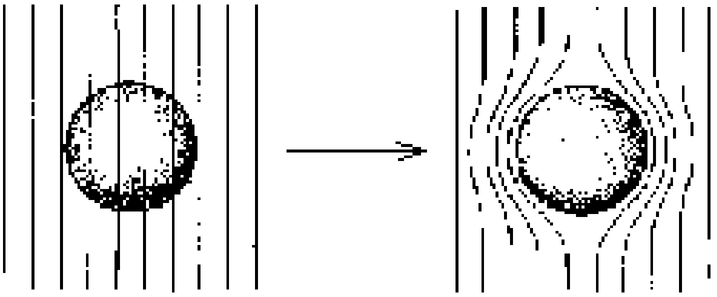

Fig. 1.5. Meissner effect in a superconducting ball, cooled in an external magnetic field

However, this explanation is not always possible. Consider the case when the sample is introduced into a magnetic field above the critical temperature, i.e., it does not possess superconducting properties. Then the lines of induction permeate it, as shown in Figure 1.5. Now, if we cool the sample below the transition point T_C, the induction lines should be pushed out of it (ris.1.5b). This important result can not be obtained simply from the fact that the resistance is zero. Ohm law $\vec{E} = \rho \vec{j}$ shows that when $\rho = 0$ an electric field is absent. From Maxwell equation $\partial \vec{B} / \partial t = rot \vec{E}$, it follows that the magnetic field should remain constant and can not be changed during the transition to the superconducting state. The Meissner effect is contrary to this result, which gives reason to believe that the perfect diamagnetism and the lack of resistance are essentially two independent properties of the superconducting state.

§1.3. The destruction of superconductivity by a magnetic field

Superconductivity is destroyed by sufficiently strong magnetic field. A threshold, or critical magnetic field H_C, necessary to destroy superconductivity depends on temperature. Figure 1.6 shows the dependence of the critical field on temperature for some superconductors. At the critical temperature T_C the critical field H_C is zero. With decreasing temperature it increases, and for the sample in the form of a long cylinder approximately described by the relation

$$H_C(T) = H_C(0)\left(1 - \frac{T^2}{T_C^2}\right) \qquad (1.1)$$

The difference between the free energy per unit volume in the normal and superconducting state can be obtained from the following considerations. The superconducting sample in an external magnetic field H_e less than critical H_C (the external field is the field generated by external sources in the absence of superconducting medium), is in the Meissner state where due to the screening currents external magnetic field is expelled from it. This means that according to the principle of superposition the magnetic field created by screening currents required to compensate the external field within the sample, at all points is exactly equal to the external field and is directed opposite to him. The energy density of this field is $\mu_0 H_e^2/2$, and the total free energy per unit volume is $F_S + \mu_0 H_e^2/2$. When the external field is equal to the critical H_C, the sample goes back to normal, because its energy is equal to the energy in the normal state, i.e., $F_N = F_S + \mu_0 H_C^2/2$, which implies

$$F_N - F_S = \mu_0 H_C^2/2 \qquad (1.2)$$

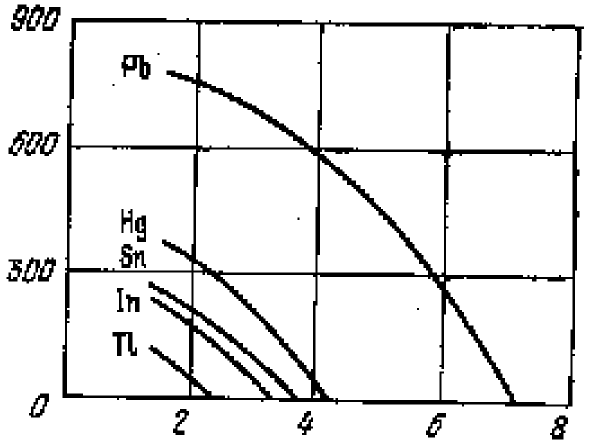

Fig. 1.6. Field dependence of the critical temperature for some superconductors.

§1.4. Type of phase transition

In the absence of an external magnetic field the superconducting transition is a phase transition of the second type, i.e., it occurs without liberation or absorption of heat. At the same time, in full accordance with the theory of this transition, the specific heat at the transition point is discontinuous.

The situation is different if the process takes place in an external magnetic field. In this case, during the transition from the superconducting state to the normal some heat must be absorbed and vice versa. In other words, in a magnetic field a phase transition is of the first type.