§1.8. Stationary and non-stationary Josephson effects

In the previous paragraph we considered tunneling of separate electrons through the isolating layer. But, as we will see further, in a superconductor electrons are united in Cooper pairs. Therefore it is natural to assume that in the case of contact of two superconductors through rather thin layer of dielectric also pairs of electrons can tunnel. B. Josephson was the first who considered this effect in 1962. For these works in 1973 he was awarded by Nobel Prize. He showed that the tunneling of Cooper pairs becomes essential at a thickness of barrier of 10-20 angstrom. Besides, he predicted some unusual and interesting phenomena taking place when electrons tunnel in pairs. Subsequently all his predictions were excellently confirmed on experiment. Besides their basic value for understanding of superconductivity the Josephson effects (it is accepted to call this complex of the phenomena) give the opportunities for carrying out the most exact measurements. We will emphasize that they play especially important role in the processes occurring in the high temperature ceramic superconductors because in them Josephson contacts already exist naturally (contacts between granules). For this reason these substances sometimes are called Josephson mediums.

The stationary effect of Josephson is a percolation of not fading superconducting current through a thin isolating layer at a zero voltage on contact. The magnitude of such current can't be more than some critical value I_C.

The non-stationary Josephson effect appears at a nonzero voltage U_S on the contact. In this case a high-frequency alternating current percolates through the contact which frequency ν is proportional to the voltage:

$$\nu = \frac{2eU_S}{h} \qquad (1.10)$$

To understand a practical situation, we will consider the chain represented in fig. 1.14. When a constant superconducting current flows through the contact (stationary effect of Josephson) the voltage on contact is equal to zero, i.e. all U_S falls on the resistance R. This regime can exist if the current (equal to U_S/R) does not exceed the critical value I_C. Thus, the stationary effect of Josephson takes place if $U_S < I_C R$. If $U_S > I_C R$, the generation of high-frequency current begins. Then the mathematical description of a chain becomes very difficult.

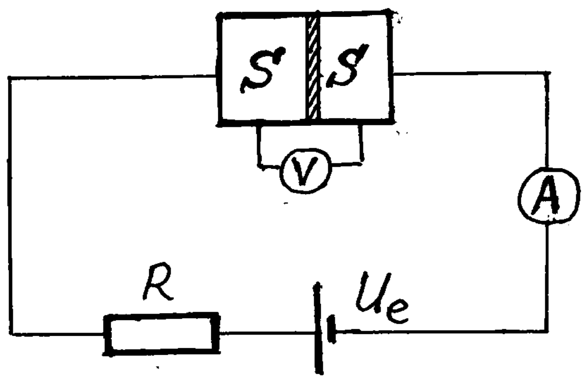

Fig. 1.14. The scheme for demonstration of Josephson effects.

§ 1.9. Quantization of magnetic flux

Let us consider a superconducting ring. It is possible to excite current in it by electromagnetic induction (for example, as shown in fig. 1.4). This current will remain invariable for unlimited time. It could seem that the corresponding selection of a magnetic field magnitude gives the chance to receive any value of the induced current. However it is not so. Current in a ring can accept some discrete values. This situation was formulated clearly by F.London. He came to a conclusion that the magnetic flux penetrating a superconducting ring has to be equal to an integer of so-called quanta of a magnetic flux Φ_0. The situation is similar to Bohr model of an atom in which the possible electronic states correspond to the values of the angular moment equal to an integer of Planck constants.

Quantum of a magnetic flux Φ_0, according to London, is equal to h/e, where h is the Planck constant, and e - the elementary charge. This conclusion was based on an assumption that electric current is transferred by separate electrons. However subsequently it appeared that current is transferred by Cooper pairs, i.e. particles with a charge 2e. Therefore the quantum of a flux appeared twice less:

$$\Phi_0 = \frac{h}{2e} = \frac{\pi\hbar}{e} \approx 2\cdot 10^{-15} Wb \qquad (1.11)$$

The predictions of London were excellently confirmed by experiment.

It is important to note that the condition of flux quantization formulated above is fair regardless of, whether the magnetic flux, penetrating a ring, is created by an external magnetic field or by the current in the ring itself. In the presence of an external field, the superconducting currents in the ring will be distributed so that the total magnetic flux through the ring was equal to an integer of flux quanta.

Quantization of a magnetic flux, and also Josephson effects considered in the previous paragraph, are a consequence of so-called “phase coherence” of all the Cooper pairs. From the point of view of quantum mechanics all pairs are in one quantum state, i.e. are coordinated among themselves in all physical parameters, in particular, in phases. This phase correlation extends on very big (practically unlimited) distances. Thus, all these effects are purely quantum phenomena, but, unlike the majority of such phenomena which are shown in a microcosm (atoms, molecules, etc.), they take place in macroscopic systems.

§1.10. Isotopic effect

In search of an explanation of effect of superconductivity experimenters investigated dependence of critical temperature on various parameters. In particular, the question of, whether a crystal lattice influences superconductivity or it is connected only with system of electrons, started being investigated in 1922 by Onnes. Very witty idea was the basis for research: various isotopes of the same element having different masses are identical from the point of view of electronic structure. Therefore detection of dependence of critical temperature on a type of an isotope would prove that the lattice also participates in creation of a phenomenon of superconductivity. The first experiments didn't show such dependence, but as a result of development of physics there appeared the possibilities of receiving in sufficient quantities the isotopes with noticeably differing masses. In 1950 such dependence was discovered by several groups of physicists. At change of mass of atom of an isotope of mercury from 199,5 to 203,4 a.m.u. the critical temperature changed from 4,185 K to 4,146 K.

Already the elementary qualitative arguments made by Frelikh allowed to expect that the critical temperature had to be inversely proportional to a square root from an atom mass:

$$T_c \sim M^{-0,5} \quad (1.12)$$

Later the theory of BCS has confirmed this result. However the accounting of thinner effects can lead to deviations from this formula.

The discovery of isotopic effect has confirmed the influence of fluctuations of a lattice on superconductivity and directed searching of the theory of superconductivity to electron - phonon interactions that, finally, has led to creation of the theory of BCS.

§1.11. Application of superconductors

Questions of various uses of superconducting materials began to be discussed practically right after discovery of the phenomenon of superconductivity. Still Kamerling-Onnes considered that by means of superconductors it was possible to create economic installations for receiving strong magnetic fields. However real use of superconductors began in the 50th − the beginning of the 60th years of the XX century. Now superconducting magnets of various sizes and forms work. Their application is beyond purely scientific researches, and today they are widely used in laboratory practice, in accelerating equipment, tomographs, installations for the operated thermonuclear reaction. By means of superconductivity it has become possible to increase sufficiently the sensitivity of many measuring devices. Such devices are called SQUID (from English Superconducting Quantum Interference Devices). Especially it is necessary to emphasize introduction of SQUID in techniques and in modern medicine.

Superconductors found the greatest application in the field of creation of strong magnetic fields now. The modern industry makes from type II superconductors the various wires and cables used for production of windings of superconducting magnets by means of which one can create much stronger fields (more than 20 T) than when using iron magnets. Superconducting magnets are also more economic. For example, for maintenance the magnetic field of 100 kGs in the copper solenoid with an internal diameter of 4 cm and 10 cm long the electric power not less than 5100 kW is necessary. And all this power has to be taken away with the water cooling. It means that through a magnet it is necessary to pump over not less than 1 m^3 of water per minute, and then still to cool it. In superconducting option such volume of a magnetic field is created rather simply, only the construction of the helium cryostat is necessary for cooling of windings, but that is a simple technical task.

Other advantage of superconducting magnets consists that they can work in the autonomous mode, without external sources.

One more application of superconductors − creation of bearings and supports without friction. If we place a superconducting sphere over a metal ring with current, due to Meissner's effect, on the surface of the sphere the superconducting current appears. As a result some forces of repulsion between the ring and the sphere emerge, and the sphere can hang over the ring. The similar effect can be observed if to place a permanent magnet over a superconducting ring. Creation, for example, of new means of transport can be based on this effect. It permits to create a train on a magnetic pillow in which there are no losses on friction about a road track. The model of such superconducting road 400 m long was constructed in Japan in the 1970th. Calculations show that the train on a magnetic pillow will be able to gather speed to 500 km/h. Such train will "hang" over rails at distance of 2−3 cm, what will give it the chance to move with such velocity.

Now superconducting volume resonators which Q-factor can reach $5 \cdot 10^{11}$ are widely used.

Use of superconductivity can lead to creation of superfast electronic computers. It is about so-called cryotrons − the switching superconducting elements. Such devices can easily be combined with the superconducting memorable elements. Important advantage of cryotrons in comparison with ordinary semiconductor devices is absence of need for energy in a steady state. After creation of Josephson contacts it was offered to replace by them cryotrons, and it appeared that time of switching of such systems makes about 10^{-12} seconds. It opens wide prospects for creation of the most powerful computers.

The most perspective directions of wide use of high-temperature superconductors are the cryoenergetic and the cryoelectronic engineering. In cryoenergetics a method of manufacturing sufficiently long (up to several kilometers) wires and cables based on bismuth HTSC materials has been developed. It is already enough for production of small engines with a superconducting winding, superconducting transformers, inductance coils etc.

In cryoelectronics the technique of production of film SQUID which according to the characteristics practically are not worse than helium analogs is developed. The technique of producing perfect magnetic screens from HTSC, in particular, for research of biomagnetic fields is mastered. Many different electronic devices, such as antennas, transferring lines, resonators, filters, frequency mixers etc. are created with use of HTSC.