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Lecture for M. Sc. Physics IV Semester students

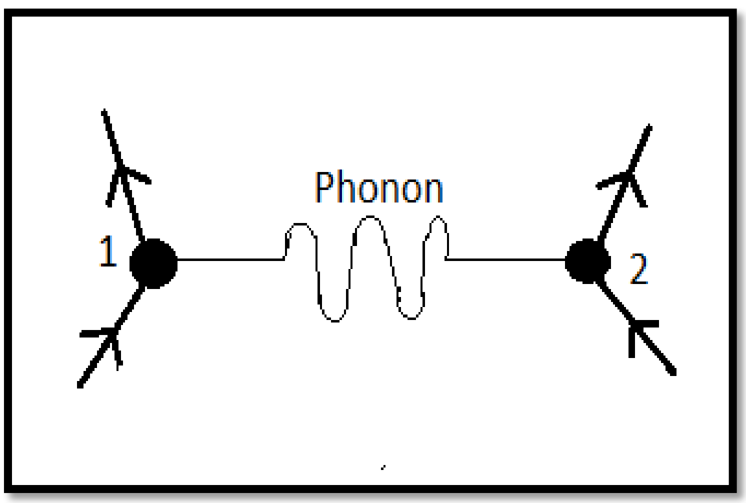
Paper-I: Condensed Matter Physics

Unit 4-: Superconductivity

Qualitative Explanation

Since electron 1 is near the Fermi surface, its speed is great. At the same time the ions, because of their heavy mass, respond rather slowly. By the time they have felt and completely responded to electron 1, electron 1 has left its initial region, at least partially, thus stimulating the over compensation. One can also reason that this process is most effective when electron 1 and 2 move in opposite directions.

We know that each electron is surrounded by a 'phonon cloud' and that the two electrons establish an attractive interaction by exchanging phonons; for example, electron 1 emits phonons which are very quickly absorbed by electron 2.



Since the phonon is involved twice- once in emission and once in absorption- the attraction between electrons is a second order process.

Tunneling and The Josephson Effect

When a thin junction involving a superconductor is prepared, tunneling may take place across the junction and the tunneling current may be used to study the physical properties of the superconductor.

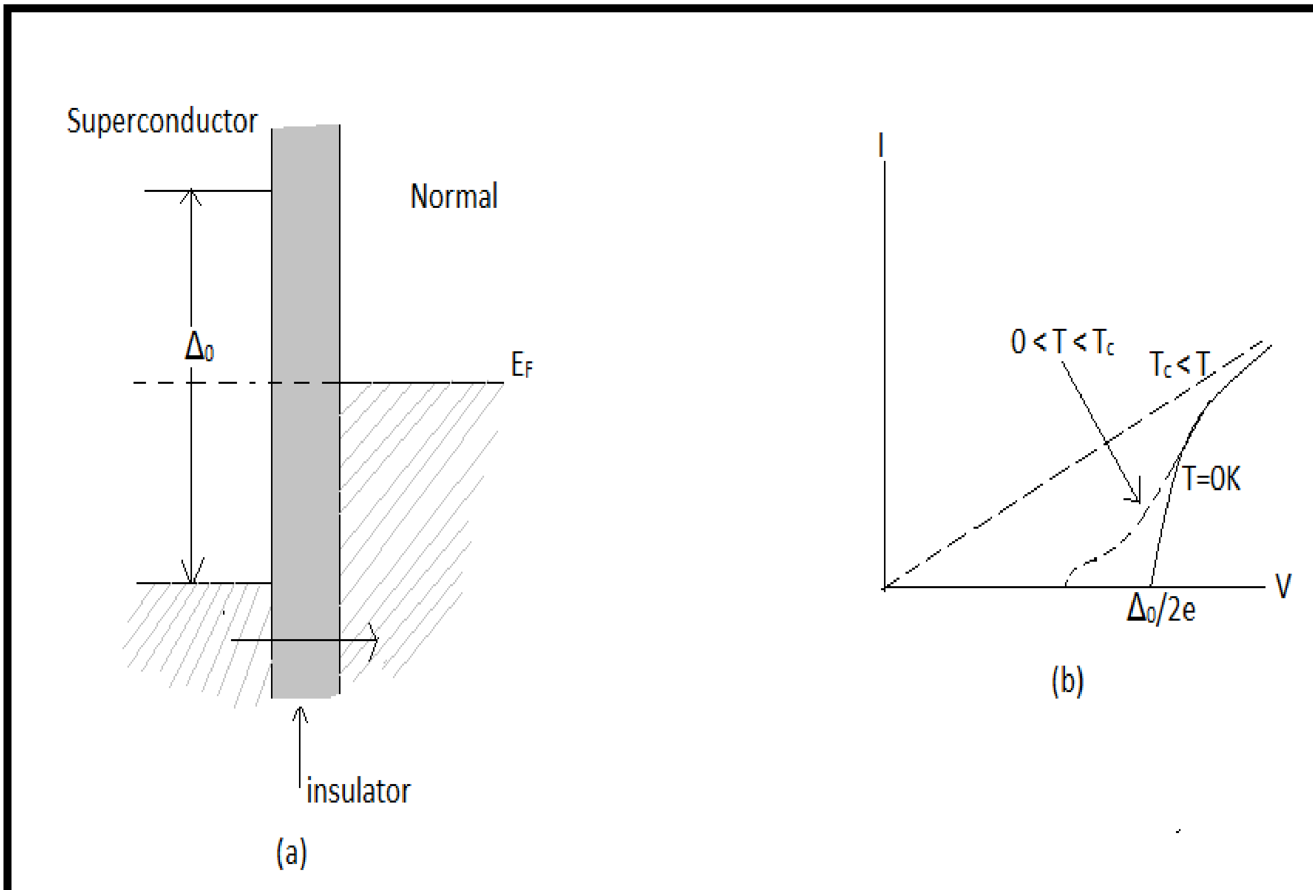


Figure (a) shows such a junction, in which two pieces of metal, in the superconducting and normal state, respectively, are joined by a thin insulating film of thickness of about 50Å. The film acts as a potential barrier as far as the flow of electrons across the junction is concerned, but because the film is thin, it does not completely inhibit the flow. According to quantum mechanics, electrons are still able to tunnel under a thin potential barrier.

If a small voltage V is applied across the junction (taking the field to be directed to the left), the energy band of the left side is raised by the amount eV, but the electrons are still unable to flow to the right because the states lying horizontally across are already occupied.

But if the voltage is increased further so that the energy band of the superconductor is raised by ${}^{\Delta_0}/_2$, then the corresponding horizontal states on the right are now empty, and the current proceeds to flow. This results in the I-V characteristics shown in figure (b). The voltage at which the current begins to flow is such that

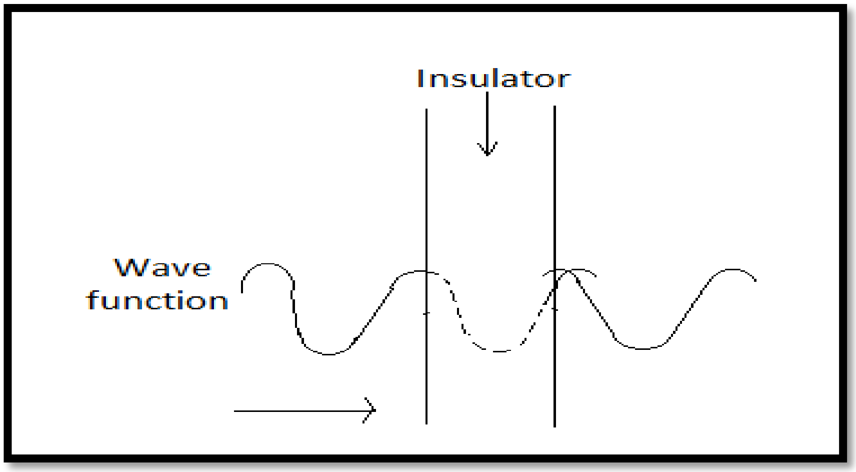
$$ {}^{\Delta_0}/_2 = \mathrm{eV} \qquad \text{.................. (1)} $$

and from this the superconducting gap may be determined.

The above tunneling is referred to as normal or single electron tunneling, because single electron tunnel to the right.

Another type of tunneling, one which involves Cooper pairs, has received a great deal of attention recently, and is responsible for the Josephson Effect.

The underlying principle is that if the insulating film is very thin-i.e. about 10Ǻ – then the pairs would not tunnel readily across the junction, but also their wave functions on both sides would be highly correlated. In fact, the effect of the film is merely to introduce a phase difference Φ_0 between the two parts of the wave function on opposite sides of the junction as shown below:



The current density across the junction is given in terms of this phase by the relation

$$J = J_1 sin\,\Phi_0, \qquad \text{.......... (2)}$$

Where J_1 is a measure of the probability of transition across the junction.

In absence of any potential difference across the junction, the phase Φ_0 adjusts its value to that of the actual current so that eq (2) is satisfied.

Let us now suppose that a static potential V_0 is applied across the junction. We recall from quantum mechanics that the phase of the wave function in quantum mechanics is

$$\Delta\Phi = \frac{\mathrm{Et}}{\hbar} \qquad \text{............. (3)}$$

where E is the total energy of the system.

Let us now apply this to calculate the additional phase difference experienced by the Cooper pair as it tunnels across the junction. In this case $E = (2e)\,V_0$, in which the factor 2 is introduced because the system here involves a pair of electrons. Therefore

$$\omega = \frac{2\mathrm{e}V_0}{\hbar} \qquad \text{................ (4)}$$

which now alters (2) to the new form

$$J = J_1 \sin(\Phi_0 + \Delta\Phi)$$

$$= J_1 \sin(\Phi_0 + \frac{2eV_0 t}{\hbar}) \qquad \text{………….. (5)}$$

which represents an alternating current. This result is interesting because a static potential is seen to lead to an ac current and the frequency

$$\omega = \frac{2eV_0}{\hbar} \qquad \text{……….. (6)}$$

is readily tuned by varying V_0. Numerically

$$\vartheta = 484\, V_0\, GH_z$$

for V_0 in millivolts.

Since V_0 is usually of the order of several millivolts, the Josephson frequency falls in the microwave range.

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