Experimental Study on the Conditions for Observing the Josephson Effect as a Method for Discovering the Type of Electron Pairing in Superconductors

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In this paper an experiment to identify the type of pairing of electrons in superconductors is suggested. Its result will help to find out whether there is attraction between the electrons of the system leading to the appearance of bound pairs or there is just a feature of the correlation energy of a pair of electrons at the same or adjacent nodes of the momenta grid.

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I. INTRODUCTION

The Josephson effect holds a special place in theoretical physics. It could hardly be denied that it was the prediction of this effect, as well as its subsequent interpretation and observation, that led to the recognition of the BCS theory as the standard theory of superconductivity.

However, in 1964, doubts arose in the scientific community about the consistency of the Josephson effect interpretation in the BCS theory. The essence of these doubts was as follows.

If parameters \((u, v)\) in the Bogoliubov transformation are replaced with \((u \exp(iϕ), v \exp(-iϕ))\), the equations for them within the limits of the variational procedure existing in the BCS theory will still be valid. This is not surprising, because such a transformation corresponds to the unitary transformation \(\exp(iϕ \hat{N})\) of the basis set of the system wave functions, where \(\hat{N}\) is the operator of total number of electrons in the system.

On the other hand, consider the two superconductors contacting through the tunneling Hamiltonian. If we apply transformation \(\exp(iϕ_1 \hat{N}_1)\) to the basis set of wave functions of the first superconductor, and transformation \(\exp(iϕ_2 \hat{N}_2)\) - to that of the second superconductor, then it is possible to calculate the second-order correction to the energy of the system of two superconductors, which appears to depend on the phase difference \(ϕ_2 - ϕ_1\). This is contrary to the principles of quantum mechanics, because the values of observables should not depend on the choice of the basis set of the wave functions of systems.

The analysis shows that the cause of the described paradox is the symmetry breaking of the original Hamiltonian upon the transition to the model single-particle Hamiltonian written in the creation and annihilation operators of so-called bogolons. Unfortunately, proponents of the BCS theory decided to use the observed paradox for the interpretation of the Josephson effect instead eliminating the paradox.

Recently, it was found that the theory of He II can be constructed without using anomalous expectation values. It should also be noted that paper \(\text{[6]}\) has completed a series of works on the creation of an alternative theory of superconductivity (ATS), which did not use anomalous expectation values either and, therefore, did not contain paradoxes, including the interpretation of the Josephson effect. In such a situation one can say that both the recognized superfluidity theory and the superconductivity theory have serious competitors.

A significant difference of the ATS as compared to the BCS theory is the lack of attraction between electrons even after taking into account electron-phonon interaction. In fact, only the specific feature of the correlation energy of electron pairs situated at the same node or at adjacent nodes of the momenta grid (cf. Eq.(14)\(\text{[8]}\)) can be interpreted as attraction. This energy is derived from the interaction potential between the electrons. In such a situation bosonization of the electronic system is impossible. The lack of bosonization leads to the fact that the Josephson effect does not have to be observed if a Josephson junction (JJ) is connected to a voltage source. In particular, it is easy to show that, if a JJ (here and below we consider the superconductor-insulator-superconductor structures) is connected a capacitor not bridged with metal conductors, then, according to the ATS, only voltage-dependent current will be observed, and not phase-dependent current. That is, Giaever tunneling will take place. Thus, it is easy to show that a condition for the existence of the Josephson current in the ATS is the presence of

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continuous wave functions of the basis set for the electronic states along the chain contour that includes a JJ. Of course, the electron wave functions are interrupted on the plates of the capacitor.

However, if there is attraction between electrons, it provides the possibility of pair formation leading to the system bosonization. At low temperatures a Bose condensate is formed, and in such a system the Josephson effect is observed, even if a JJ is connected to a charged capacitor. In fact, the occupation number of the state with the lowest energy becomes macroscopic at temperatures below the Bose condensation temperature. As a result, the matrix elements of the tunneling transition connecting the states with the lowest energy are much greater than the matrix elements corresponding to other transitions. In such circumstances, we need only consider a transition between two orbitals. This problem was considered by Feynman [10]. Of course, the results clearly confirm the earlier assumption that the Josephson effect in systems with bosonization is observed, even when a JJ is connected to a charged capacitor not bridged with metallic conductors.

The formal application of the BCS theory shows that the Josephson current should be observed if a JJ is connected to a charged capacitor, and the paradox discussed in the beginning of the article plays a crucial role. This assumption is also evidenced by the situation with the superfluid $^3$He. Thus, it is believed that it is the BCS theory that describes superfluidity in $^3$He. At the same time, in the experiment on the Josephson effect in $^3$He the wave functions of the helium atoms on the opposite sides of the tunnel junction are not connected to any circuit, where they would continuously change into one another [11]. The fact that the proponents of the BCS theory have no concern in the situation with the interpretation of the Josephson effect in superfluid $^3$He confirms the assumption that the BCS theory should predict the presence of the Josephson current in a situation where a JJ is connected to a charged capacitor.

Thus, the ATS and the BCS theory predict different results for an experiment in which a JJ is connected to a charged capacitor not bridged with a metal conductor. This enables determining the correct theory of superconductivity in a simple experiment, which will be described below.

II. EXPERIMENT DESCRIPTION

Fig. 1 shows a circuit diagram of an installation for the study of the conditions of the observation of the AC Josephson effect.

In the initial situation both keys $K1$ and $K2$ are closed, and the experimenter should find out whether the Josephson

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FIG. 1: A circuit diagram of an installation.
current is generated in the circuit. From the ATS viewpoint this is possible, if the output of the DC voltage $U$ is bridged with a resistor, which is a metal wire composing, for example, the voltage divider. It is significant to note that the signal generated by the Josephson current should be detected from resistor $R$ to avoid bridging of the JJ with the meter.

After this, keys $K_2$ and $K_1$ are sequentially opened, and capacitor $C$ becomes obviously charged. If key $K_2$ is then closed, according to the BCS theory AC will be generated, and according to the ATS this capacitor will discharge monotonically.

In order to reliably interpret the experiment results, the circuit parameters should meet the following requirements. First, voltage should be large enough to fulfill the conditions of the Josephson AC generation:

\[ U > I_c R, \]  

where $I_c$ is the JJ critical current.

The current due to Giaever tunneling will be considered to be much less than $I_c$. This situation can be obtained by simply decreasing the JJ temperature. In this case the time of the capacitor discharge $\tau$ can be estimated as follows:

\[ \tau = CU/I_c. \]  

On the other hand, the Josephson current frequency $\nu$ may be estimated as follows:

\[ \nu = \frac{2e}{\hbar} \left( U - I_c R \right). \]  

If $\tau \nu \gg 1$, the experimenter will be able to register a lot of periods of the Josephson current generation, if it arises. This condition determines a requirement for the capacitor value:

\[ C \gg \frac{I_c h}{2eU (U - I_c R)}. \]  

### III. CONCLUSION

In this paper an experiment to identify the type of pairing of electrons in superconductors is suggested. Its result will help to find out whether there is attraction between the electrons of the system leading to the appearance of bound pairs or there is just a feature of the correlation energy of pair of electrons at the same or adjacent nodes of the momenta grid. Such a feature is predicted by the alternative theory of superconductivity [6].

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