Feynman diagrams to explain superconductivity in YBCO

Kizka V.A.

Joint Institute for Nuclear Research, Dubna, 141980, Russia
kizkavaleri@gmail.com

Abstract. Using the Feynman diagrams, I tried to explain the existence of a pseudogap in YBCO and why below the critical temperature, the YBCO sample has zero resistivity, but a finite value of the superconducting current flowing through the sample.

Keywords: Feynman diagram, pseudogap temperature, Cooper pair.

1. Introduction

Today, a strange situation is observed in the theory of superconductivity, which manifests itself in the fact that there are no attempts to give an answer to the elementary question - why does the final current flow in a superconductor sample with its zero resistivity?

To answer this paradoxical question, without delving into the quantum theory of superconductivity, I tried to look at the form of a function that satisfactorily describes the experimental dependence of the sample resistivity on temperature. In this case, the analysis must necessarily include the region of zero values of the resistivity of the sample at $T < T_c$, which is completely ignored in all works where they focus only on the region of nonzero values of the resistivity function on temperature. At the second stage, looking at the resulting function, I assumed which mechanism is responsible for each part of the function and how it can be depicted in the form of a Feynman diagram.

2. Fitting experimental data

For the analysis, the initial graphics of the dependence of the resistivity of the YBCO sample A on temperature was selected [1] and the fitting was performed with a function of the form:

$$\rho_{fit} = \frac{p_0}{\sum_{i=1}^{9}{}' \frac{p_i}{(T + p_{i+1})^{(i+1)/2}}}, \qquad (1)$$

where p_i are constants; the prime at the summation sign means that i runs through only odd values, i.e. i = 1, 3, 5, 7, 9.

Figure 1 shows the result of fitting the experimental data for the resistivity of the YBCO sample A (points [1]) by function (1).

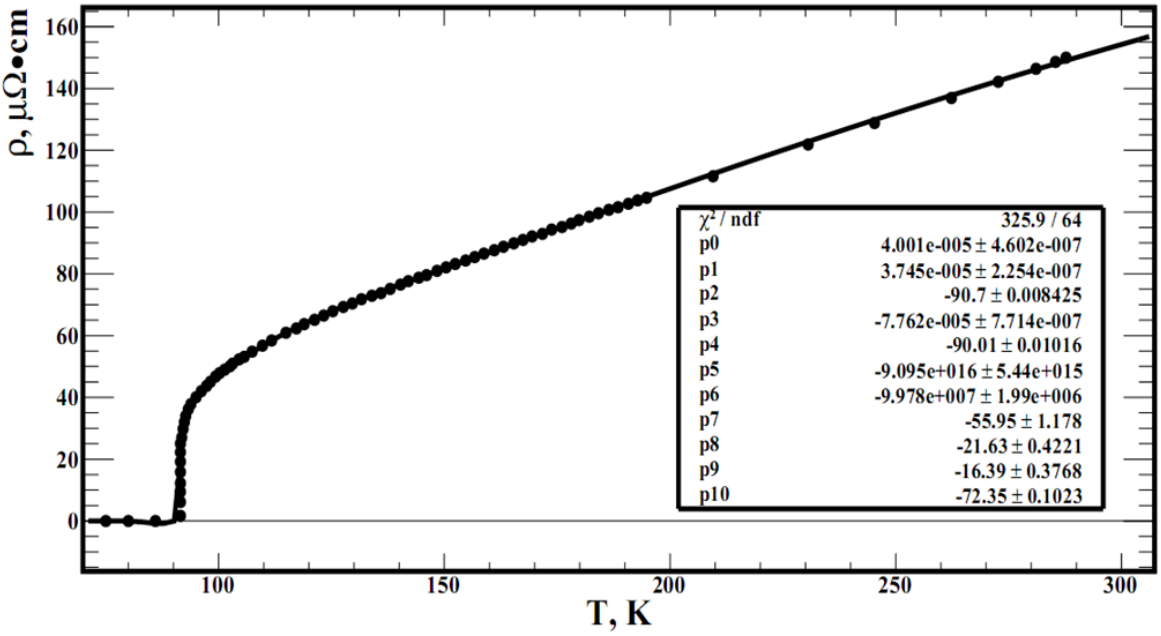

Fig.1. Fitting the experimental data for the resistivity of the YBCO sample A (points are from [1]) to curve (1) with the coefficients p_i (and p_{i+1}) indicated in the inset.

The type of excess conductivity $\Delta\sigma = \frac{1}{\rho} - \frac{1}{\rho_n} \equiv \sigma'$ from [2] makes it possible to represent a superconductor in the form of an electrical equivalent circuit of parallel connection of two resistivities ρ_n (normal) and $\rho' = \frac{1}{\Delta\sigma}$ associated with excess conductivity (or through resistances R_n and $R^{'}$) (Fig.2a). And the total conduction $\frac{1}{R} = \frac{1}{R_n} + \frac{1}{R^{'}}$. At T < T_c R = 0, and the current remains finite, which means that a current source must be switched on with intrinsic resistance equal to zero, that is we assume ideal current source (Fig. 2b). Since the intrinsic resistance of an ideal current source is zero, the current passes through it, bypassing the normal R_n and excess $R^{'}$ branches.

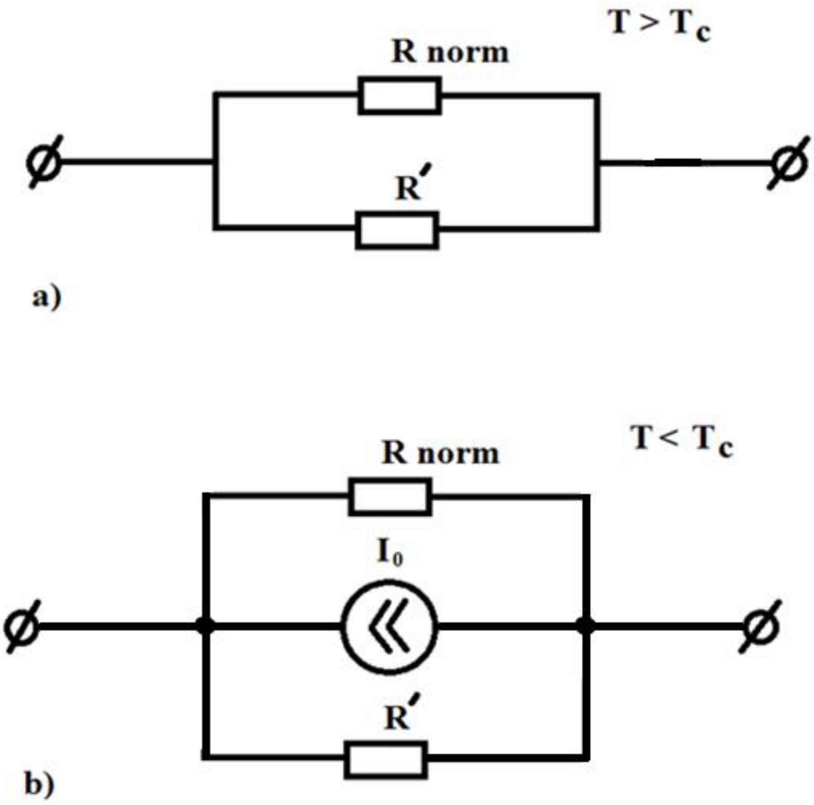

Fig. 2. Electric equivalent circuits of a YBCO superconductor: a) at $T > T_c$; b) at $T < T_c$.

3. Feynman diagram construction

The normal electron e_1 interacts with the ion of crystal lattice through a phonon or photon, and the ion re-emits a phonon or photon - process *3* in Fig.3. Let us assume that the phonon, re-emitted by the ion, is scattered by the electron e_2 and again absorbed by the electron e_1 or another electron e_3 - processes *1* and *2*, respectively (Fig.3). It is clear that process *3* is the usual friction of an electron against the crystal lattice, which determines R_n, and processes *1* and *2* determine the excess conduction $1/R'$, since friction e_1 is immediately compensated by the creation of a Cooper pair. On the other hand, process *4* (Fig.3) is most likely completely suppressed by lattice vibrations and takes effect only at $T < T_c$, when process *4* becomes dominant, representing an ideal current source (Fig.2b) and the amplitudes of the first three processes remain nonzero.

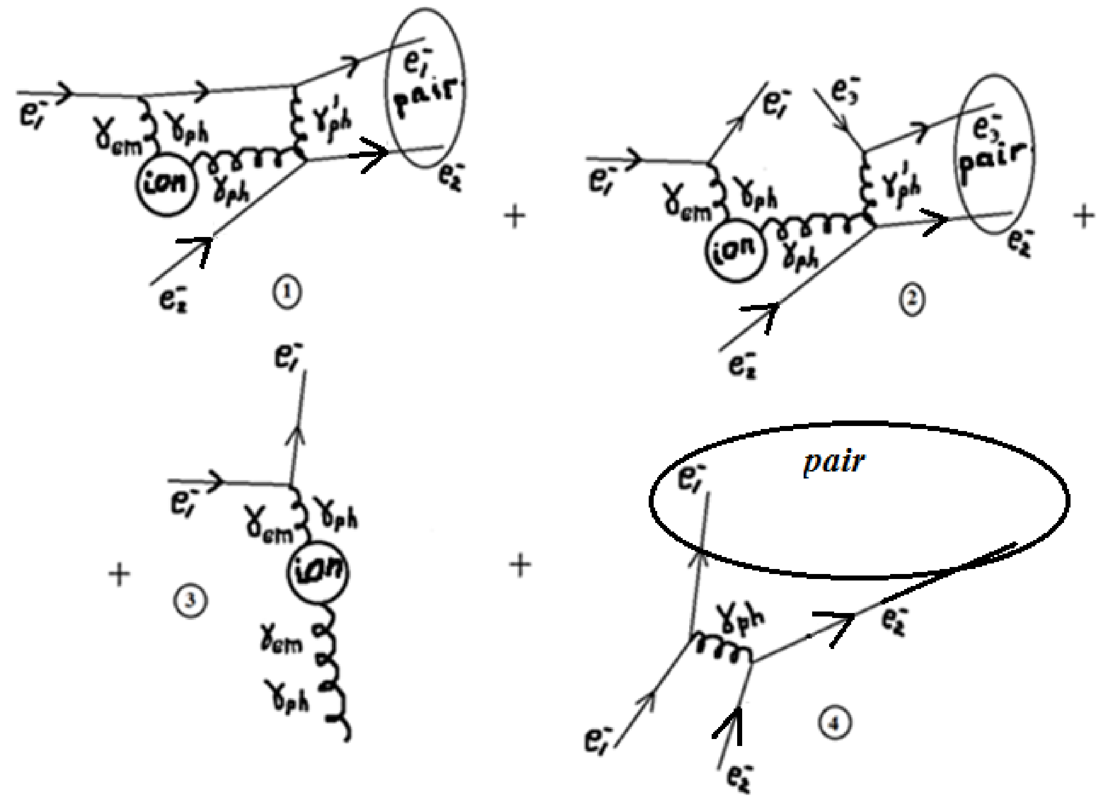

Fig. 3. Processes *1* and *2* determine the excess conductivity at $T < T^*$ (pseudogap temperature), reducing the process of friction of the conduction electron against the crystal lattice (process *3*), taking away the re-emitted phonon for the formation of a Cooper pair. At $T < T_c$, process *4* is switched on. The possibility of emission of a phonon or photon is indicated by the symbols of a phonon γ_{ph} and a photon γ_{em} next to the propagator.

Now it would be natural to describe the experimental points for ρ of T from [1] at $T > T_c$ using *5* terms of formula (1), each of which is responsible for its own process of interaction of electrons with the crystal lattice and with each other:

$$\frac{1}{\rho} = \frac{1}{\rho_n} + \frac{1}{\rho'} + \frac{1}{\rho''} + \frac{1}{\rho'''} + \frac{1}{\rho''''} \qquad (2a)$$

or

$$\rho = \frac{1}{\frac{1}{\rho_n} + \frac{1}{\rho'} + \frac{1}{\rho''} + \frac{1}{\rho'''} + \frac{1}{\rho''''}}. \qquad (2b)$$

Here, process *3* (Fig.3) is responsible for the normal resistivity ρ_n; the process *1* is for excess conductivity, that is for ρ', process *2* is for ρ'', and we assume the existence of other diagrams of a larger order (Fig.4) for the last two resistivities - ρ''' and ρ''''. Second-order processes responsible for the fourth and fifth terms in (2a) can be represented by the diagrams shown in Fig.4. At $T < T_c$ $\rho = 0$ due to process *4*, which appears at these temperatures as the sixth term in (2) for a current source with an internal resistivity equal to zero:

$$\rho = \frac{1}{\frac{1}{\rho_n} + \frac{1}{\rho'} + \frac{1}{\rho''} + \frac{1}{\rho'''} + \frac{1}{\rho''''} + \frac{1}{0}} = 0. \qquad (3)$$

4. Conclusion

It can be assumed that at $T > T^*$ (pseudogap temperature), process *3* (Fig.3) is dominant and unique. At $T^* > T > T_c$, processes *1* and *2* (including second-order processes) are switched on, which causes a decrease in the resistivity of the superconductor, since this is equivalent to the parallel connection of other resistivities. Or it can be said that at these temperatures $T^* > T > T_c$, part of the collisions of normal electrons with the crystal lattice is compensated by the formation of superconducting electrons (Cooper pairs). At $T < T_c$, all collisions of normal electrons with the crystal lattice are compensated by the formation of Cooper pairs not only by processes *1* and *2* (including second-order processes), but also by process *4*. The latter is equivalent to the parallel connection of an ideal current source to normal and hatched resistivities.

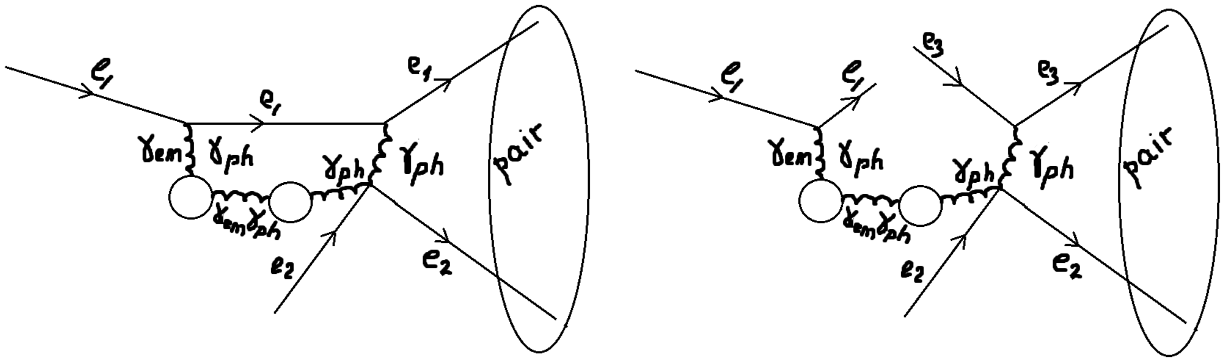

Fig. 4. Second-order diagrams of electron scattering on crystal lattice appeared at $T < T^{*}$. The possibility of emission of a phonon or photon is indicated by the symbols of a phonon γ_{ph} and a photon γ_{em} next to the propagator.

References

[1] Solovjov, A.L., Petrenko, E.V., Omelchenko, L.V. et al. “Effect of annealing on a pseudogap state in untwinned $YBa_2Cu_3O_{7-\delta}$ single crystals”. Sci Rep 9, 9274 (2019). https://doi.org/10.1038/s41598-019-45286-w

[2] B. Leridon, A. Défossez, J. Dumont, J. Lesueur, and J. P. Contour “Conductivity of Underdoped $YBa_2Cu_3O_{7-\delta}$: Evidence for Incoherent Pair Correlations in the Pseudogap Regime” Phys. Rev. Lett. 87, 197007 (2001). https://doi.org/10.1103/PhysRevLett.87.197007