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RESEARCH ARTICLE

Transmission coefficients of superconducting particles

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Abstract

Objectives. *There is no general theory of superconductivity capable of fully describing this phenomenon, which imposes its own difficulties in the search for new superconducting materials, as well as in the study of their properties. In particular, the electrodynamics of a superconducting system is unexplored. With the aim of a possible further description of the electrodynamics of superconductors, the temperature dependences of the energy parameters of a Cooper pair in the potential field of Abrikosov vortex were analyzed.*
Methods. *The basis for the obtained results of the work was the consideration of the transmission coefficient for a superconducting particle in the approximation of the Wentzel–Kramers–Brillouin method, as well as the relationship between the critical temperature and the London penetration depth and the coherence length based on the model of plasmon destruction of the superconducting state.*
Results. *The dependences of the lifetime of a particle in a potential well, penetration depth, frequency of impacts of a particle against a potential barrier, blurring of the energy level, transmission coefficient, and potential and kinetic energy of a particle on temperature were obtained. The characteristic values of these parameters were obtained at absolute zero for various cuprate, organic, and other superconducting materials. The dependences of the critical electric potential on temperature, as well as the London penetration depth, coherence length, and electric potential on the transmission coefficient at different temperatures were obtained. The form of the dependences qualitatively corresponds to the experimental data.*
Conclusions. *The results obtained can be used to construct a general theory of superconductivity, describe the electrodynamics of a superconducting state, and develop new superconductors with higher critical currents.*

Keywords: *theory of superconductivity, Cooper pair, Abrikosov vortex, electrodynamics of superconductors*

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НАУЧНАЯ СТАТЬЯ

О коэффициенте прохождения сверхпроводящей частицы

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Аннотация

Цели. *Общая теория сверхпроводимости, способная полностью описать данное явление, отсутствует, что накладывает свои трудности в поиске новых сверхпроводящих материалов и исследовании их свойств. В частности, неисследованной является электродинамика сверхпроводящей системы. С целью возможного дальнейшего описания электродинамики сверхпроводников в работе рассматриваются температурные зависимости энергетических параметров куперовской пары в потенциальном поле вихря Абрикосова.*
Методы. *Основой для полученных результатов работы являлось рассмотрение коэффициента прохождения сверхпроводящей частицы в приближении метода Вентцеля–Крамерса–Бриллюэна, а также связь критической температуры с лондоновской глубиной проникновения и длиной когерентности на основе модели плазмонного разрушения сверхпроводящего состояния.*
Результаты. *Получены зависимости времени жизни частицы в потенциальной яме, глубины проникновения, частоты ударов частицы о потенциальный барьер, размытости энергетического уровня, коэффициента прохождения, потенциальной, кинетической энергии частицы от температуры. Получены характерные значения данных параметров при абсолютном нуле для различных купратных, органических и других сверхпроводящих материалов. Получены зависимости критического электрического потенциала от температуры, лондоновской глубины проникновения, длины когерентности; электрического потенциала от коэффициента прохождения при разных значениях температуры. Вид зависимостей качественно соответствует экспериментальным данным.*
Выводы. *Полученные результаты могут быть использованы для построения общей теории сверхпроводимости, описании электродинамики сверхпроводящего состояния, разработки новых сверхпроводников, обладающих более высокими значениями критических токов.*

Ключевые слова: *теория сверхпроводимости, куперовская пара, вихрь Абрикосова, электродинамика сверхпроводников*

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INTRODUCTION

Based on the works of Abrikosov [1] and the discovery of Abrikosov vortices, the electrodynamics of the superconducting state is mainly described through the motion of the vortex lattice [2]. Mechanical models of motion consider the forces of viscous friction, pinning of vortices, and forces that deform the lattice. However, this approach does not consider the quantum nature of the Abrikosov vortex and the phenomenon of superconductivity. Another common approach to describing the dynamics of the superconducting state is the solitonic theory of superconductivity [3]. This approach considers nonlinear excitations, which often leads to difficulties in obtaining an accurate solution, and although the solitonic theory accounts for some differential characteristics of cuprate superconductors it does not apply to all superconducting materials.

The absence of a general theory describing the electrodynamics of the superconducting state means that to give a generalized theoretical description of the current–voltage characteristics of most superconducting compounds, which is extremely important for their wider application, is difficult.

In this study, we analyze a model of the motion of a Cooper pair in an Abrikosov vortex. This problem has been considered [4] using a framework that estimated the relationship between the coherence length and London penetration depth, as well as solving the one-dimensional Schrodinger equation, which is important for constructing a general theory of superconductivity and the electrodynamics of the superconducting state. We investigated the dependences of various energy parameters of a superconducting particle on temperature, including its transmission coefficient, which formed the basis of a qualitative model describing the current-voltage characteristics of superconductors.

TEMPERATURE DEPENDENCES OF THE ENERGY PARAMETERS OF THE COOPER PAIR IN THE POTENTIAL FIELD OF THE ABRIKOSOV VORTEX

We estimated the dependence of the transmission coefficient of a superconducting particle D through the potential barrier of the Abrikosov vortex U. The region of the Abrikosov vortex where the energy of a superconducting particle can be efficiently dissipated is the non-superconducting inner cylindrical region. In this region, one can assume that the energy of the Abrikosov vortex is constant in the limit $\xi << \lambda$, where ξ is the coherence length, which is the characteristic size of the Cooper pair, and λ is the London penetration depth, which is the characteristic depth of penetration of the external magnetic field into the superconductor. [5] Then, using the quasi-classical Wentzel–Kramers–Brillouin approximation [6], we obtained the following expression for the transmission coefficient:

$$D(T) = \frac{e^{-4\xi(T)\sqrt{\frac{2m}{\hbar^2}(U(T)-E(T))}}}{(1+0.25e^{-4\xi(T)\sqrt{\frac{2m}{\hbar^2}(U(T)-E(T))}})^2}, \tag{1}$$

where m is the mass of the Cooper pair (in this paper it is twice the mass of the electron), $\hbar$ is the Dirac constant, and E is the energy of the Cooper pair.

The potential energy is the energy of the Abrikosov vortex, which is generally expressed in terms of the Bessel function K_0 [5] and is often normalized to a certain unit of length. In this paper, the coherence length was used as the unit of length:

$$U(T) = \frac{\Phi_0^2 \xi(E)}{4\pi\mu_0 \lambda(T)^2} K_0\left(\frac{\xi(T)}{\lambda(T)}\right), \tag{2}$$

where Φ_0 is the magnetic flux quantum, μ_0 is the magnetic constant, and λ is the London penetration depth.

Using the analogy of an energy gap, the energy of a superconducting particle can be expressed as $E = 2kT_c$, where T_c is the critical temperature, i.e., the temperature at which a material transitions to the superconducting state. Building on the relationship between the critical temperature, London penetration depth, and coherence length obtained in [7], we expressed the particle energy in terms of these characteristic lengths:

$$E(T) = \hbar c \big/ \lambda(T) \sqrt{\frac{4\pi\alpha\xi(T)}{\lambda(T)}}, \tag{3}$$

where c is the speed of light and α is the fine structure constant.

The dependences of the measured ξ and λ on temperature were determined using standard expressions:

$$\xi(T) = \frac{\xi(0)}{\sqrt{1-\left(\frac{T}{T_c}\right)^4}}, \tag{4}$$

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1-\left(\frac{T}{T_c}\right)^4}}, \tag{5}$$

We plotted the dependences of the energies and the transmission coefficient on the temperature for the $YBa_2Cu_3O_7$ superconductor at $\lambda(0)$ = 180 nm, $\xi(0)$ = 0.4 nm, and T_c = 90.8 K [8] (Figs. 1 and 2).

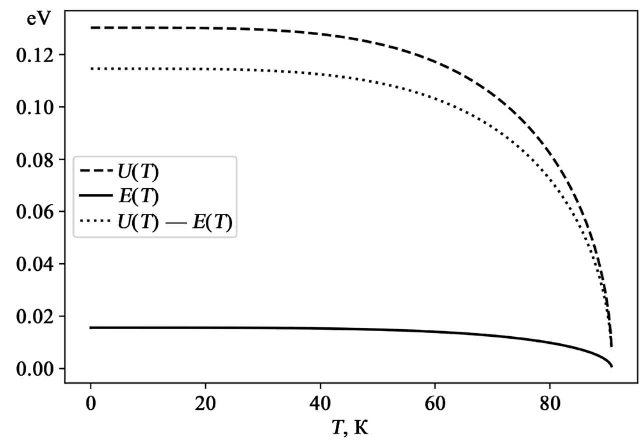

Fig. 1. Dependence of the potential, U, and kinetic, E, energies and the energy difference on temperature for $YBa_2Cu_3O_7$.

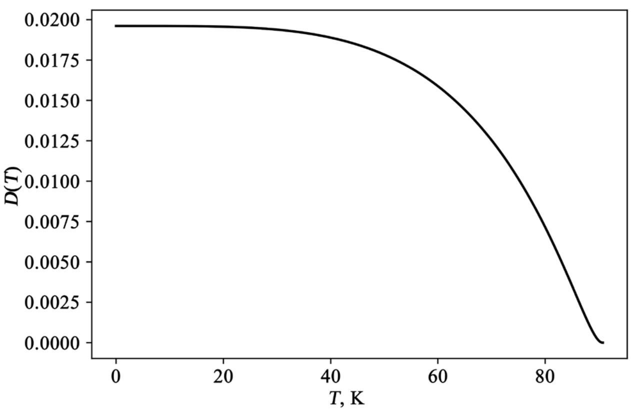

Fig. 2. Dependence of the transmission coefficient on temperature for $YBa_2Cu_3O_7$.

Based on the obtained transmission coefficient, we were able to obtain the dependence of the frequency of the particle impacting on the barrier *n*, the lifetime of the particle in the well *t*, the depth of penetration under the potential barrier *L*, and the blurring of the energy level on the temperature *T* [6]:

$$n(T) = \frac{1}{4\lambda(T)}\sqrt{\frac{2E(T)}{m}} \quad (6)$$

$$t(T) = \frac{1}{n(T)D(T)} \quad (7)$$

$$L(T) = \frac{\hbar}{2\sqrt{2m(U(T)-E(T))}} \quad (8)$$

$$\Delta E(T) = h / t(T) \quad (9)$$

From this we found that the potential and kinetic energies of the particle, the transmission coefficient, the number of collisions per unit time, and the blurring of the energy gap decreased with increasing temperature; however, the penetration depth and lifetime of the Cooper pair in the non-superconducting region of the vortex increased with increasing temperature.

We then calculated the characteristic values of (1)–(3), (6), (8), and (9) for cuprate, organic, and some other type-II superconductors at $T = 0$ K (Table 1). For this analysis, materials were selected which validated the expression (3) and corresponded with the calculated (T_c*) and experimental (T_c) critical temperatures (Table 2).

Based on the obtained dependence of the transmission coefficient of the Cooper pair on temperature, we constructed a qualitative model for describing the current-voltage characteristics of superconductors.

In the first approximation we assumed that the energy of the Abrikosov vortex does not depend on

Table 1. Typical values of the energy parameters of some superconductors at $T = 0$ K

Material	$D(0)$	$U(0)$, eV	$E(0)$, eV	$n(0)$, s^{-1}	$L(0)$, m	$\Delta E(0)$, eV
$La_{1.85}Sr_{0.15}CuO$	0.021	0.042	5.606×10^{-3}	1.827×10^{10}	3.623×10^{-10}	1.567×10^{-6}
$YBa_2Cu_3O_7$	0.02	0.13	0.016	7.29×10^{10}	2.04×10^{-10}	5.909×10^{-6}
$Bi_2Sr_2CuO_{6+x}$	1.55×10^{-3}	0.025	3.234×10^{-3}	7.457×10^{9}	4.638×10^{-10}	4.779×10^{-8}
$Bi_2Sr_2CaCu_2O_{8+x}$	2.636×10^{-11}	0.193	0.016	4.459×10^{10}	1.642×10^{-10}	4.86×10^{-15}
$HgBa_2CuO_{4+x}$	9.739×10^{-7}	0.175	0.016	5.325×10^{10}	1.734×10^{-10}	2.144×10^{-10}
$HgBa_2CaCu_2O_{6+x}$	1.242×10^{-12}	0.336	0.027	8.337×10^{10}	1.24×10^{-10}	4.281×10^{-16}
$HgBa_2Ca_2Cu_3O_{8+x}$	6.248×10^{-11}	0.318	0.026	8.437×10^{10}	1.277×10^{-10}	2.18×10^{-14}
κ-(BEDT-TTF)$_2$Cu(NCS)$_2$	0.108	0.011	1.794×10^{-3}	4.623×10^{9}	7.366×10^{-10}	2.059×10^{-6}
(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br	0.233	0.01	1.928×10^{-3}	5.883×10^{9}	7.534×10^{-10}	5.674×10^{-6}
β_L-(BEDT-TTF)$_2$|$_3$	0.088	2.098×10^{-3}	4.08×10^{-4}	6.055×10^{8}	1.68×10^{-9}	2.21×10^{-7}
β-(BEDT-TTF)$_2$|Br$_2$	1.164×10^{-64}	0.014	1.121×10^{-3}	7.025×10^{8}	5.978×10^{-10}	3.382×10^{-70}
β-(BEDT-TTF)$_2$|Au$_2$	8.041×10^{-23}	0.011	1.002×10^{-3}	8.302×10^{8}	7.076×10^{-10}	2.760×10^{-28}
CNT(5,0)	1.139×10^{-13}	0.027	2.59×10^{-3}	3.513×10^{9}	4.429×10^{-10}	1.654×10^{-18}
$NbSe_2$	5.705×10^{-4}	0.012	1.626×10^{-3}	2.82×10^{9}	6.695×10^{-10}	6.653×10^{-9}
H_2S(155 HPa)	1.471×10^{-18}	0.468	0.034	1.019×10^{11}	1.047×10^{-10}	6.200×10^{-22}

Note: BEDT-TTF is bis(ethylendithio)tetratiafulvalen and CNT(5,0) is a carbon nanotube with a chirality of (5,0).

Table 2. Comparison of the calculated (T_c*) and experimental (T_c) critical temperatures of various superconductors

Material	ξ, nm	λ, nm	T_c^*, K	T_c, K	Reference
$La_{1.85}Sr_{0.15}CuO$	0.7	430	32.5	34	[8]
$YBa_2Cu_3O_7$	0.4	180	90.8	92.4	[8]
$Bi_2Sr_2CuO_{6+x}$	1.5	800	18.8	13	[9]
$Bi_2Sr_2CaCu_2O_{8+x}$	2	200–300 at 300	94.3	94	[9]
$HgBa_2CuO_{4+x}$	1.2	200–450 at 252	94.9	95	[9]
$HgBa_2CaCu_2O_{6+x}$	1.7	205	154	127	[9]
$HgBa_2Ca_2Cu_3O_{8+x}$	1.5	130–200 at 200	150	135	[9]
κ-(BEDT-TTF)$_2$Cu(NCS)$_2$	0.8	500–2000 at 961	10.41	10.4	[9]
(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br	0.5–1.2 at 0.5	550–1500 at 783	11.19	11.2	[9]
β_L-(BEDT-TTF)$_2$|$_3$	2	3500	2.37	1.5	[9]
β-(BEDT-TTF)$_2$|Br$_2$	44–46 at 44	4000–5000 at 5000	6.5	2.2	[9]
β-(BEDT-TTF)$_2$|Au$_2$	18–25 at 18	4000	5.81	4.2	[9]
CNT(5,0)	6.6–12 at 6.6	1430–1570 at 1520	15.03	15	[10]
$NbSe_2$	2.5	1500	9.44	7	[9]
H_2S(155 HPa)	2.15	189	195.56	190–203	[11]

the external applied electric field, allowing us to add to the energy of the particle E the dependence on the applied potential φ as follows: $E(T, \varphi) = E(T) + 2q\varphi$, where q is the charge of the electron.

Then the critical electric potential was defined as $\varphi_c = (U - E)/2q$ (Fig. 3). We also determined the dependence of the critical potential on the characteristic lengths that determine the superconducting state (Fig. 4).

The dependence of the electric potential on the transmission coefficient at different temperatures is shown in Fig. 5, which physically represents a qualitative description of the current-voltage characteristic of superconductors.

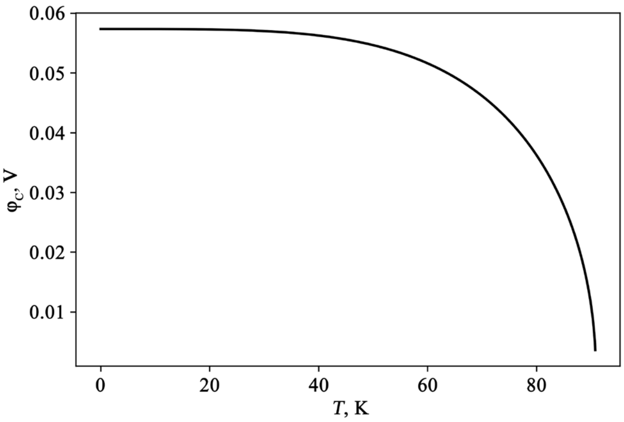

Fig. 3. Dependence of the critical electric potential (φ_c) value on temperature for $YBa_2Cu_3O_7$.

RESULTS AND DISCUSSION

The obtained dependences of various energy parameters of superconducting materials were mainly expressed in terms of the characteristic lengths that determine the superconducting state, the London penetration depth, and the coherence length. The determination of the transmission coefficient was obtained based on the dependence of the characteristic lengths on temperature, which is not generally described by equations in the form of (4) and (5) [12] but instead requires specific consideration for a particular superconducting material.

We found that the considered dependence of the particle energy on temperature has a similar form to the dependence of the energy gap on temperature.

According to our obtained characteristic values of the energy parameters shown in Table 2, we concluded that some organic materials with large London penetration depths, as well as H_2S, are significantly knocked out of the materials. These organic materials are less accurately described by the expression for the critical temperature given in [7], which may indicate

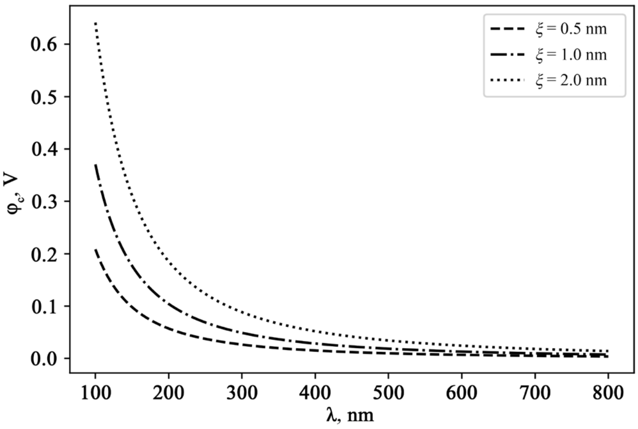

Fig. 4. Dependence of the value of the critical electric potential (φ_c) on the London depth of penetration for various fixed coherence lengths.

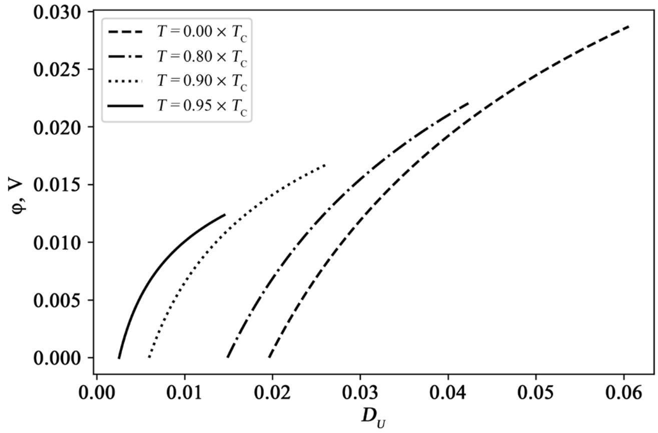

Fig. 5. Dependence of the electric potential on the transmission coefficient at different temperatures for $YBa_2Cu_3O_7$.

that their effective characteristic lengths match the experimental critical temperatures more closely. The obtained values for H_2S indicate that superconducting properties around room temperature require an increase in the energy of the Abrikosov vortex.

The direct proportionality of the transmission coefficient to the tunnel current means that the obtained dependence φ(D) (Fig. 5) has a direct relationship with the current-voltage characteristics of superconducting materials and, as we have demonstrated, has a similar form to experimental measurements in this area [13, 14].

In this study, the dependence on the electric potential φ was given by adding the kinetic energy required to accelerate the particles; however, to improve the accuracy of the model, we found that it was necessary to determine all the dependences on external factors for the parameters of a superconducting material through the dependences on the London penetration depth and coherence length. Despite this, the obtained dependence of the critical potential on the temperature has a form that can describe the experimental data but can also easily be reduced to the traditional linear dependence of the critical current on the temperature in the region of the phase transition of the Bardeen-Cooper-Schrieffer theory [15] and experimental power approximations. The critical electric potential, as well as the kinetic energy of the superconducting particle and its critical temperature, increased with increasing coherence length and decreased with increasing London penetration depth.

CONCLUSIONS

In this study, the dependences of various energy parameters on temperature were obtained with the dependence of the transmission coefficient being especially relevant to the future construction of a general theory of the electrodynamics of superconductors.

The characteristic values of these energy parameters can be used to evaluate the fundamental and applied properties associated with the mechanisms of superconductivity.

The obtained dependences of the critical electric potential on temperature and the transmission coefficient qualitatively matched the corresponding experimental measurements and can be used to construct a theory of superconductivity, which itself can be used to develop new superconductor based current-conducting devices. In the future, we regard the dependence of the characteristic lengths on the electric potential to be of interest in the building of a more accurate model of the current-voltage characteristics of superconductors.

Authors' contribution

The contribution of each of the authors was to jointly set tasks, solve them, and discuss the results. The authors made an equal contribution to the calculation part of the work, the preparation of the article for publication, and the use of software to create a visualization of the obtained dependencies.

The authors declare no conflicts of interest.

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