Effect of symmetry of the electron states of HTSC on the current-voltage characteristics of SIS junctions.

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Abstract

The current-voltage $IV$ characteristics of $SIS$ junctions are calculated in the framework of a multiband model with an anisotropic effective order parameter of HTSC. The results of calculations show that the shape of $IV$ characteristic and the density of electron states changes significantly depending on the parameters of the model. A theoretical explanation is proposed for the experimentally observed $s$-like behavior of the $IV$ characteristics of $SIN$ and $SIS$ junctions with BSCCO-type superconductors. The dependence of the superconducting peaks asymmetry on the mutual arrangement of the bands is analyzed. The difference between the obtained results and the results of single-band models with the $s$ and $d$ symmetries of the order parameter is discussed.

The lack of a generally accepted explanation of the pairing mechanism in high-temperature superconductors (HTSC) makes the interpretation of numerous experimental data (including the results of tunnel experiments) difficult. The complexity of the crystal structure of HTSC compounds also complicates the situation. In most cases, it is difficult to explain peculiarities in the tunnel characteristics within the framework of the standard Bardeen-Cooper-Schrieffer (BCS) model. Such peculiarities include the variety of the subgap structure ranging from a linear $d$-type structure to a nearly planar structure of the $s$ type [1], the asymmetry of superconducting peaks at the edge of the gap [2, 3], and nontrivial behavior of the tunnel density of states of $SIN$ junctions and of the current-voltage characteristics of $SIS$ junctions outside the gap region. In some experiments [4, 5], strongly suppressed $dI/dV$ characteristics with very narrow peaks typical of $s$-type superconductors were obtained in the subgap region, which contradict at first glance the available data on strong anisotropy of the order parameter in the $CuO_2$ plane [6].

A large number of theoretical models have been proposed to explain the variety of experimental data. These include the models based on various features of the band structure (taking into account, for example, the closeness of the Van Hove singularities to the chemical potential [7, 8]), on the choice of the order parameter symmetry [8], and on the properties of the tunnel matrix element [9] in the single-band BCS scheme. Even the slave-boson approach [10] was used for explanation the asymmetry of the superconducting peaks and the inhomogeneity of the density of electron states in the normal state. A series of publications [11, 12, 13, 14] is devoted to the role of inelastic scattering, including the inelastic scattering by antiferromagnetic spin fluctuations. The results of theoretical investigations show that the inclusion of Van Hove singularities and the use of the $(s + d)$ symmetry of the order parameter are obviously
essential for a correct explanation of the most experimentally observed properties of the tunnel conductivity of HTSC. For this reason, the experimental investigation of the properties of the electron spectrum of high-temperature superconductors in the normal state is very important.

In our opinion, it is the analysis of the crystal structure that makes it possible to explain a number of results of tunnel measurements in high-temperature superconductors. This paper aims at explanation the features of tunnel characteristics using the model with an anisotropic effective order parameter, which is based only on the properties of the electron spectrum of HTSC \[15\]. The spectrum of the considered model approximately corresponds to the band structure of compounds of the BiSrCaCuO (BSCCO) type. An important feature of this approach is that the initial electron-electron interaction leading to pairing is treated as isotropic in the \(CuO_2\) plane. The anisotropy of the order parameter and of the excitation spectrum is determined by the symmetry properties of the crystal lattice. According to our calculations, many features of the tunnel characteristics typical of HTSC compounds can be explained by using a rather universal approach which will be described below.

Let us consider the effect of symmetry of the initial bands of the superconductor on the current-voltage characteristics of \(SIS\)-junctions. The electron system of the \(CuO_2\) plane is described by model Hamiltonian of the form:

\[
H = \varepsilon_z^z \sum_{i,\sigma} c_{i,\sigma}^\dagger c_{i,\sigma} + \varepsilon_d \sum_{i,\sigma} d_{i,\sigma}^\dagger d_{i,\sigma} + \varepsilon_p \sum_{i,\sigma} (p_x^j(i,\sigma)p_x(i,\sigma) + p_y^j(i,\sigma)p_y(i,\sigma)) +
+ \sum_{i,j,\sigma} (t_{i,j}^{ij} p_{i,\sigma} p_{j,\sigma} + h.c.) + \sum_{i,j,\sigma} (t_{i,j}^{ij} p_{i,\sigma} p_{j,\sigma} + h.c.) +
+ \sum_{i,j,\sigma} (t_{i,j}^{ij} d_{i,\sigma}^\dagger p_{j,\sigma} + h.c.) + \sum_{i,j,\sigma} (t_{i,j}^{ij} d_{i,\sigma}^\dagger p_{j,\sigma} + h.c.) +
+ U_{zz} \sum_i c_{i,\sigma}^\dagger c_{i,\sigma}^\dagger c_{i,\sigma} c_{i,\sigma} + U_d \sum_i d_{i,\sigma}^\dagger d_{i,\sigma}^\dagger d_{i,\sigma}^\dagger d_{i,\sigma}^\dagger , \tag{1}
\]

Here \(c_{i,\sigma}^\dagger\) and \(d_{i,\sigma}^\dagger\) are creation operators for electrons with spin \(\sigma\) on the \(d_{x^2}\) and \(d_{x^2-y^2}\) orbitals of the \(i\)-th site of copper; \(p_x^j(i,\sigma)\) and \(p_y^j(i,\sigma)\) are the creation operators for electrons with spin \(\sigma\) on the \(p_x\) and \(p_y\) orbitals of the \(i\)-th site of oxygen (Fig.1). \(\varepsilon_p, \varepsilon_d\) and \(\varepsilon_z\) are the energies of the \(p\) levels of oxygen and of the \(d_{x^2-y^2}\) and \(d_{x^2}\) levels of copper, respectively, measured from the chemical potential \(\mu = 0\). \(t_{i,j}^{ij}\text{ and } t_{i,j}^{ij}\text{ are the matrix elements of one-particle transitions between the } d_{zz} \text{ and } d_{x^2-y^2} \text{ orbitals of } \) copper and the \(p\) orbitals of oxygen. For the sake of simplicity, we assume that superconductivity is caused by the isotropic attraction \(U_{zz} < 0\) of electrons on the \(d_{zz}\) orbital. It should be noted that a more complicated consideration of the superconducting interaction would not lead to a qualitative difference from the case investigated here. We also assume the presence of the isotropic effective electron-electron interaction \(U_d\) on the \(d_{x^2-y^2}\) orbital of copper.

Introducing new operators \(a_{k,\sigma}^{(\beta)}(\beta=1,2,3)\) in the \(k\) representation according to the formulas

\[
d_{k,\sigma} = C^{(1)}_{d} a_{k,\sigma}^{(1)} + C^{(2)}_{d} a_{k,\sigma}^{(2)} + C^{(3)}_{d} a_{k,\sigma}^{(3)}
\]

\[
p_x(k,\sigma) = C^{(1)}_{p_x} a_{k,\sigma}^{(1)} + C^{(2)}_{p_x} a_{k,\sigma}^{(2)} + C^{(3)}_{p_x} a_{k,\sigma}^{(3)} \tag{2}
\]

\[
p_y(k,\sigma) = C^{(1)}_{p_y} a_{k,\sigma}^{(1)} + C^{(2)}_{p_y} a_{k,\sigma}^{(2)} + C^{(3)}_{p_y} a_{k,\sigma}^{(3)} ,
\]
we diagonalize the Hamiltonian part describing one-particle transition between the $d_{x^2-y^2}$ orbitals of copper and the $p$ orbitals of oxygen. The coefficients $C_d$ and $C_{p_x(p_y)}$ in formulas (2) have the form:

$$C_d^{(1)} = 0,$$

$$C_{p_x(p_y)}^{(1)} = \frac{\mathbf{t}_y(x)}{\sqrt{(t_x)^2 + (t_y)^2}},$$

$$C_d^{(\alpha)} = \frac{\varepsilon_p - \varepsilon_\alpha}{\sqrt{(\varepsilon_p - \varepsilon_\alpha)^2 + (t_x)^2 + (t_y)^2}},$$

$$C_{p_x(p_y)}^{(\alpha)} = \pm \frac{t_x(y)}{\sqrt{(\varepsilon_p - \varepsilon_\alpha)^2 + (t_x)^2 + (t_y)^2}},$$

where $\alpha = 2, 3$ and $t_{x(y)} = t_{d-p} \sin \frac{k_{x(y)}}{2}$. Similarly, the matrix element of a transition between the $d_{x^2-y^2}$ orbitals of copper and the $p$ orbitals of oxygen in the $\mathbf{k}$ representation can be written as $\tilde{t}_{x(y)} = t_{z^2-p} \sin \frac{k_{z^2-p}}{2}$. Since the matrix elements $t_{x(y)}^{j^\dagger}$ and $t_{z^2-p}^{j^\dagger}$ depend on the indices of different sites, the quantities $t_{x(y)}$ and $\tilde{t}_{x(y)}$ must be functions of $\mathbf{k}$. Operators $a_{k,\sigma}^{(1)+}$, $a_{k,\sigma}^{(2)+}$ and $a_{k,\sigma}^{(3)+}$ are the creation operators for electrons with spin $\sigma$ and quasimomentum $\mathbf{k}$ in the bands formed by hybridized $p$ orbitals of oxygen and $d_{x^2-y^2}$ orbitals of copper with the dispersion relation

$$\varepsilon_1 = \varepsilon_p, \quad \varepsilon_{2(3)}(\mathbf{k}) = \frac{\varepsilon_p + \varepsilon_d}{2} \pm \frac{1}{2} \sqrt{(\varepsilon_p - \varepsilon_d)^2 + 4(t_x^2(\mathbf{k}) + t_y^2(\mathbf{k}))}. \quad (3)$$

As a result of transformation (2), the system Hamiltonian in the mean-field approximation takes the form:

$$H = \sum_{k,\sigma} \varepsilon_{z^2} c_{k,\sigma}^+ c_{k,\sigma} + \sum_{k,\sigma,\beta} \varepsilon_\beta a_{k,\sigma}^{(\beta)+} a_{k,\sigma}^{(\beta)}$$

$$+ \sum_{k,\sigma,\beta} (W_\beta(\mathbf{k}) c_{k,\sigma}^+ c_{k,\sigma}^{(\beta)} + h.c.)$$
where

\[
W_1(k) = -\frac{\tilde{t}_x t_y + \tilde{t}_y t_x}{\sqrt{t_x^2 + t_y^2}}, \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \q
In the following, we will make use of quasiparticle density of states of the $z^2$ band,

$$N(\omega) = -\frac{1}{\pi} \int \frac{d^3 k}{(2\pi)^3} \text{Im} G^R_{z^2}(\omega, k).$$

(13)

The retarded Green’s function is obtained by the solution of the system of equations (8-11) and has the form:

$$G^R_{z^2}(\omega, k) = \frac{u_{-}^2}{\omega - E_-(k) + i0} + \frac{u_{+}^2}{\omega - E_+(k) + i0} + \frac{v_{-}^2}{\omega + E_-(k) + i0} + \frac{v_{+}^2}{\omega + E_+(k) + i0},$$

where the coherence factors are defined as

$$u_{\pm}^2 = \pm \frac{(E_- + \varepsilon_{z^2})(-E^2_z + \varepsilon_z^2 + \Delta_3^2) + W_3^2(E_- - \varepsilon_3)}{2E_-(E_+^2 - E_-^2)}$$

and

$$v_{\pm}^2 = \pm \frac{(E_- - \varepsilon_{z^2})(-E^2_z + \varepsilon_z^2 + \Delta_3^2) + W_3^2(E_- + \varepsilon_3)}{2E_-(E_+^2 - E_-^2)}.$$

The dispersion relations for two branches of the excitation spectrum have the form

$$E_{z^2}^2(k) = \frac{\varepsilon_{z^2}^2(k) + \Delta_{z^2}^2 + \varepsilon_3^2(k) + \Delta_3^2(k) + 2W_3^2(k)}{2}$$

$$\pm \sqrt{\left(\varepsilon_{z^2}^2(k) + \Delta_{z^2}^2 - \varepsilon_3^2(k) - \Delta_3^2(k)\right)^2 + 4W_3^2(k)\left(\left(\Delta_{z^2} - \Delta_3(k)\right)^2 + \left(\varepsilon_{z^2}(k) + \varepsilon_3(k)\right)^2\right)}}$$

(14)

The set of equations (8-11) can be reduced to the system of two equations for Green’s functions $G_{z^2}$ and $F_{z^2}$ with the effective order parameter defined by the formula

$$\Delta_{z^2}(k) = \frac{\Delta_3(k)W_3^2(k)}{\varepsilon_3^2(k) + \Delta_3^2(k)} + \Delta_{z^2}.$$

(15)

The sign of the order parameter $\Delta_3(k)(12)$ is determined by the sign of the parameter $\Delta_d(7)$, which can be positive or negative depending on the type of interaction $U_d$ (repulsion or attraction). The parameter $\Delta_d = 0$ if $U_d = 0$ or $U_d > U_d^{\text{crit}} > 0$, where $U_d^{\text{crit}}$ is a certain critical value of repulsion on the $d_{x^2-y^2}$ orbital of copper which suppresses superconductivity in the system. As seen from the formula (15), in the case of a nonzero interaction $U_d$ on the $d_{x^2-y^2}$ orbital ($\Delta_d \neq 0$), the order parameter depends on quasimomentum, and in the case of repulsion, $\frac{\Delta_3(k)}{\Delta_{z^2}} < 0$ ($U_d > 0$), the parameter $\Delta_{z^2}(k)$ changes its sign.

The approach considered explains the strong anisotropy of the order parameter as a consequence of the symmetry properties of the one-particle matrix element of the interband hybridization $W_3(k)$ [15], which has nodes along the diagonals of the Brillouin zone due to the difference between the types of symmetry of the initial bands. In this case, the branch $E_-(k)$ of the excitation spectrum vanishes at points located on lines in the $k$ space [6] at which the effective order parameter $\Delta_{z^2}(k)$ is equal to zero. It should be noted that the initial interaction is regarded as isotropic; i.e., the effect considered does not depend on the origin of the pairing mechanism. In addition, the approach does not require a strong anisotropy of the spectrum and, hence, can be used for various types of high-temperature superconductors. The model proposed in [17] also leads to formulas of the type (14), (15), but it is based on the exotic condition of the interaction sign reversal in various regions of the Fermi surface.
The diagonalization of the one-particle part of Hamiltonian (1) leads to the problem with anisotropic attraction in energy bands. The effective order parameters in the bands may have nodes, but have no pure $d$ or $(s+d)$ symmetry since their anisotropy is determined by the band representations of the space symmetry group of the lattice [13, 18, 19].

The formulated model of the order parameter anisotropy makes it possible to obtain the characteristics of $SIS$ junctions for superconductors of the BSCCO type. Taking into account the crystal structure of these compounds, we will assume that tunneling along the $c$ axis occurs mainly through the $d_{xz}$ orbitals of copper in the $CuO_2$ plane (and through the apical oxygen which is not included explicitly in the model). The matrix element of tunneling is assumed to be independent of momentum ($T_{kp} = T = const$) due to the random formation of bonds between the $d_{xz}$ orbitals on both sides of the break junction. Thus, tunneling between two superconductors ($CuO_2$ layers) is treated as occurring through a number of point junctions.

The expression for the dependence of the quasiparticle tunnel current on the voltage applied to the junction in this case assumes the standard form:

$$I(V) = 4e|T|^2 \int_{-\infty}^{\infty} [n(\omega) - n(\omega - eV)] N(\omega) N(\omega - eV) d\omega,$$

where $n(\omega) = (e^{\frac{\omega}{T}} + 1)^{-1}$ is the Fermi distribution function and $N(\omega)$ is defined by formula (13). All calculations were performed for temperature $T = 0$. An important aspect of this approach is that $N(\omega)$ is not the average density of states in the conduction band (as in the single-band BCS model), but is a partial density on the $d_{xz}$ orbital.

In order to find the density of states $N(\omega)$ and the tunnel conductance $\frac{dI}{dV}$ in accordance with the chosen approximation, we used the values of parameters from the tight-binding model, which correspond to the calculations of the band structure of HTSC [20]. If all parameters are expressed in terms of $\Delta_{z^2}$ and the position of energy levels is measured from the chemical potential, we have $t_{d-p} = 75$, $t_{z^2-p} = 15$, $\varepsilon_d = -75$ and $\varepsilon_p = -50$. In all calculations, we assumed the existence of a finite relaxation constant $\gamma = 0.05$. The parameter determining the width of the initial $\varepsilon_{z^2}(k)$ band is $t_{z^2} = 1.5$.

For the chosen values of the parameters, we analyzed the behavior of the characteristics $N(\omega)$ and $\frac{dI}{dV}$ depending on the interaction value between electrons on the $d_{x^2-y^2}$ orbital of copper and on the position of the center $\varepsilon_{z^2}$ of the initial $z^2$ band relative to the chemical potential (Figs. 2-4). The obtained dependencies were compared with these of single-band model with the $s$- and $d$-types of symmetry of the order parameter ($\Delta = const$ and $\Delta \sim (\cos(k_x) - \cos(k_y))$, respectively).

Figure 2A shows the $N(\omega)$ curves calculated for the normal state ($\Delta_{z^2} = 0$). These curves display split peaks associated with the Van Hove singularities of the initial $\varepsilon_{z^2}(k)$ band for various positions of its center relative to the chemical potential, as well as the following peaks formed by singularities of the $\varepsilon_3(k)$ band. Figure 2b shows the same curves in the case when the $\varepsilon_{z^2}(k)$ spectrum is replaced by a dispersionless level ($t_{z^2} = 0$).

Figure 3A presents the $N(\omega)$ dependencies in the superconducting state for the case when the $z^2$ band is far from the chemical potential ($\varepsilon_{z^2} = -10$). It can be seen from the figure that if there is electron-electron repulsion on the $d_{x^2-y^2}$ orbital $\Delta_d = -0.5$, the density of quasiparticles is similar to that calculated in a model with the $d$ symmetry of the order parameter (in particular, it is a linear function of $\omega$ in the vicinity of $\omega = 0$). If there is no interaction on
the $d_{x^2-y^2}$ orbital, the distance between the superconducting peaks and their height increase. According to analytical estimations, $N(\omega) \sim \omega^{3/2}$ for very small frequencies. Similar results can also be obtained in the single-band model with a nontrivial spectrum and an effective order parameter of certain symmetry. As noted above, taking into account the above approximations, the diagonalization of the single-particle part of Hamiltonian (1) leads to the single-band model with anisotropic pairing. In this case, the symmetry of the corresponding order parameter can be approximated by an $(s + d)$-type symmetry.

If the center of the initial $z^2$ band is close to the chemical potential (see Figs. 3B and 3C), the difference between the $a$ and $b$ curves (with and without taking into account of repulsion) vanishes due to the dominant role of the Van Hove singularities on energy scales of the order of $\Delta_{z^2}$. In both cases, the behavior of the density of quasiparticles becomes of the $s$ type. The calculated density of states demonstrates the asymmetry of peaks, which is associated with the position of Van Hove singularities in the normal density of states (see Fig. 2). The Van Hove singularity nearest to the chemical potential increases the height of the corresponding peak in the density of states in the superconducting state. A comparison of Figs. 3B and 3C shows that, for a certain intermediate value of $\varepsilon_{z^2}$, there is the mirror switching of the asymmetry of peaks associated with the model spectrum structure.

The curves presented in Fig. 3A show that even without the repulsion on the $d_{x^2-y^2}$-orbital if the $\varepsilon_{z^2}$ level is far from the chemical potential ($\varepsilon_{z^2} = -10$), the distance between the superconducting peaks is smaller than $2\Delta_{z^2}$. As the $\varepsilon_{z^2}$ level approaches the chemical potential, the distance between the superconducting peaks increases, and the position of the peaks on the $N(\omega)$ curve for $\varepsilon_{z^2} = 0$ corresponds to the parameter $\Delta_{z^2}$. In this case, the height of the peaks increases significantly. The distance between the peaks changes as a result of the displacement of the $\varepsilon_{z^2}$ level relative to the chemical potential for the fixed values of the remaining parameters. However, a more detailed analysis of this phenomenon requires the solution of the self-consistent equations for order parameters as functions of the parameters of the model as well as the determination of the interaction constants $U_{z^2}$ and $U_d$ taking into account the specific mechanism of pairing, which is beyond the scope of the present paper. The dependence of the distance between the superconducting peaks on the position of the chemical
Figure 3: Density of states in the normal and superconducting states in the $z^2$ band: A) $\varepsilon_{z^2} = -10$, $t_{z^2} = 1.5$, B) $\varepsilon_{z^2} = -1.5$, $t_{z^2} = 1.5$, C) $\varepsilon_{z^2} = 0$, $t_{z^2} = 1.5$, D) $\varepsilon_{z^2} = -1.5$, $t_{z^2} = 0$. Curves $a$ are plotted in the absence of interaction on the $d_{x^2-y^2}$ orbital ($U_d = 0$); curves $b$ take into account the repulsion on the $d_{x^2-y^2}$ orbital ($U_d > 0$); curves $c$ plotted in a model with the $s$ symmetry of the order parameter, curves $d$ are plotted in a model with the $d$ symmetry of the order parameter; curve $e$ illustrates the normal density of states.

potential in the model with the $(s + d)$-type of order parameter symmetry was also found theoretically in [13].

A comparison of the $N(\omega)$ dependencies found in the model with single-band models with the $s$- and $d$-types of the order parameter symmetry was carried out taking into account the location of the Van Hove singularities associated with the initial $\varepsilon_{z^2}(k)$ band. This is pointed out by similar asymptotic behavior of densities of states calculated for both the normal and the superconducting state in $s$-, $d$- and considered models (see Fig. 3C) on the scales of energy higher than $\Delta_{z^2}$.

A comparison of the results presented in Figs. 3B and 3D shows that, as the width of the initial $z^2$ band determined by the parameter $t_{z^2}$ decreases ($t_{z^2} = 1.5$ in Fig. 3B and $t_{z^2} = 0$ in Fig. 3D), the heights of the superconducting peaks increases, since the singularity in the normal density of states in this case is displaced towards the chemical potential (see Fig. 2).

Figure 4 shows the $\frac{dI}{dV}$ characteristics of $SIS$ junction calculated by formula (16) using the determined $N(\omega)$ dependencies for three positions of the $\varepsilon_{z^2}$ level relative to the chemical
Figure 4: \( \frac{dI}{dV} \) characteristics for A) \( \varepsilon_{z^2} = -10, t_{z^2} = 1.5 \), B) \( \varepsilon_{z^2} = -1.5, t_{z^2} = 1.5 \), C) \( \varepsilon_{z^2} = 0, t_{z^2} = 1.5 \), D) \( \varepsilon_{z^2} = -1.5, t_{z^2} = 0 \). Curves a are plotted in the absence of interaction on the \( d_{x^2-y^2} \) orbital \((U_d = 0)\); curves b take into account the repulsion on the \( d_{x^2-y^2} \) orbital \((U_d > 0)\); curves c plotted in a model with the \( s \) symmetry of the order parameter, curves d are plotted in a model with the \( d \) symmetry of the order parameter.

potential \( \varepsilon_{z^2} = -10, \varepsilon_{z^2} = -1.5, \varepsilon_{z^2} = 0 \), which can correspond to different HTSC types. The common feature of these characteristics is that in the case of repulsion the superconducting peak appears at lower voltages and is lowered, but the curve at low voltages lies higher than in the absence of interaction on the \( d_{x^2-y^2} \) orbital of copper. If the center of the initial \( z^2 \) band is far from the chemical potential \((\varepsilon_{z^2} = -10)\), the \( \frac{dI}{dV} \) characteristics are similar to those calculated in a model with the \( d \) symmetry of the order parameter (Fig. 4a). As the \( \varepsilon_{z^2} \) level approaches the chemical potential, the curves tend to the dependencies obtained in the model with the \( s \) symmetry of the order parameter (Figs. 4b and 4c). For low voltages \( V < \Delta_{z^2} \), the \( IV \) characteristic of an \( SIS \) junction is strongly suppressed. In analogy with the \( N(\omega) \) dependencies, the \( \frac{dI}{dV} \) characteristics exhibit extremely narrow superconducting peaks. This corresponds to a number of experimentally observed results for BSCCO-type compounds, e.g., optimally doped [4], overdoped [5], and underdoped [21] \( Bi_{2}Sr_{2}CaCu_{2}O_{8+\delta} \).

Thus, the electron density of states and current-voltage characteristics of \( SIS \) junctions are
calculated in the framework of the multiband HTSC model with an anisotropic effective order parameter. We took into account the hybridization between the \( d_x \) and \( d_y \) orbitals of oxygen and the \( d_{x^2-y^2} \) orbitals of copper in the \( CuO_2 \) plane and assumed the presence of electron-electron attraction on the \( d_{z^2} \) orbital of copper. The performed calculations demonstrate the possibility of explanation the results of experimental measurements of the electron density of states and the tunnel properties of \( SIN \) and \( SIS \) junctions (e.g., s-type characteristics of BSCCO-type compounds) on the basis of the model taking into account the structure of the electron spectrum of HTSC. It should be stressed that anisotropy of the order parameter and of the excitation spectrum is explained only by the symmetry of the crystal lattice and atomic orbitals and does not depend on the nature of pairing.

The main result of this work is that for a strongly anisotropic order parameter \( \Delta(\mathbf{k}) \) (15) (e.g. of \( d \)-type) and in the presence of nodes in the excitation spectrum of a superconductor, the simple inclusion of the real band structure of the HTSC in a wide range of the model parameter values results in the experimentally observed s-type behavior of the current-voltage characteristics \( SIN \) and \( SIS \) junctions. A comparison of the curves calculated for various values of the parameters of the model and in the simplest cases of models with the \( s \) and \( d \) symmetries of order parameters indicates a strong dependence of both the density of states and the \( \frac{dI}{dV} \) characteristics on the electron band structure of high-temperature superconductors. These characteristics also depend on the crystal lattice symmetry and on the presence of an additional interaction between electrons, which was introduced in the model on the \( d_{x^2-y^2} \) orbital of copper. Above analysis points to the necessity of considering of the band structure of HTSC for interpretation of the results of tunnel experiments.

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