Orthorhombic distortions may reconcile all the experimental data on YBCO.

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Abstract

A lot of controversy appeared recently in measurements of different properties of High-$T_c$-superconductor YBCO. A part of data supports d-wave hypothesis whereas other one contradicts it. We suggest to reconcile visibly controversial experimental data by an assumption that orthorombicity is not small for electronic properties of YBCO, and naturally mixes s- and d-pairing. We examine available experiments to find a proportion of such a mixture. We find in particular that the reconciliation is plausible if the Fermi-surface in YBCO is square-shaped.

74.30.Gn, 74.60.Ge
The controversy of s- and d-pairing in the High-$T_c$ superconductors attracts much attention. Exhaustive reviews of theoretical premises and experimental data has been presented recently by Dynes [1] and Schrieffer [2]. The importance of the problem is associated with the fact that d-pairing, if exists, would support the idea of the antiferromagnetic nature of the Cooper interaction. In the antiferromagnetic exchange mechanism the d-pairing occurs in a most natural way, as has been first indicated by Scalapino et al. [3] and supported with detailed calculation by Pines and coworkers [4]. Measurements of the penetration depth [4] and the nuclear magnetic resonance (see discussion in [2]) in YBCO have displayed zero or very small energy gap in the excitation spectrum. It is natural for d-pairing, and must be specially explained in the case of s-pairing. A mechanism of anisotropy enhancement in s-pairing has been proposed by Chakravarty et al. [6]. To resolve the ambiguity the experiment should answer the question, whether the order parameter changes sign on the Fermi-surface. Such an experiment with the Josephson tunneling in a special geometry has been first performed by Wollman et al. [7]. Much improved versions of this experiment have been reported recently by Brawner and Ott [8] and by Mathai et al. [9]. The most convincing is the experiment [9], in which the absence of the frozen flux and other time irreversible factors has been reliably checked. All these experiments in our opinion prove unambiguously that the order parameter changes sign on the Fermi-surface. Together with numerous experiments demonstrating the absence of the gap in the excitation spectrum ( [2], [3], [10]) they strongly support the d-pairing idea.

On the other hand, there exists a series of experiments, not less convincing which contradicts d-pairing. They are: i) Sun et al. [11] experiment on the Josephson tunneling between Pb and YBCO. If d-pairing exists, contributions to the total Josephson current from the pairs with mutually perpendicular in-plane momenta would compensate each other. In the experiment [11] a non-zero Josephson current has been observed, though rather small, 20 - 30% of what should be expected from isotropic superconductor; ii) Chaudhuri and Lin [12] has applied hexagon geometry of an YBCO sample and did not observe oscillations of current expected at d-pairing when switching off pairs of contact; iii) Valles et al. [13] and Maple
et al. [14] reported the measurements of $T_c$ vs residual resistivity $\rho$ for ion damaged and Pr substituted YBCO respectively. Their data are reasonably close each other and display a rather slow decrease of $T_c$ with increasing $\rho$. The theory ([15], [16], [17]) predicts a strong suppression of $T_c$ by elastic impurities, which effect d-superconductors in the same way as magnetic impurities effect s-superconductors [18]. For dirty anisotropic s-superconductors the theory [17] predicts a power-like decrease of $T_c$ with the residual resistivity $T_c(\rho) \sim \rho^{\kappa-1}$, where $\kappa = \langle \Delta^2 \rangle / \langle \Delta \rangle^2 > 1$ and $\langle ... \rangle$ denotes the angular average. It fits the experiment [11] within the limits of experimental errors. Kotliar and Lin [19] considered a mixture of s- and d-waves. Such a mixture can appear in principle in the strong-coupling theory. This idea has its difficulty: near the transition temperature equations for the order parameter become linear, if it is a second-order phase transition. In accordance to the Landau ideology, only one order parameter, either $d$ or $s$ can appear in the transition point. An alternative accompanying the observation $s$ and $d$-waves together is either two subsequent second-order phase transitions, or the first-order phase transition. Both contradict to the experiment.

The above consideration implies that the initial symmetry is tetragonal. It is not the case for YBCO. The symmetry is almost tetragonal in CuO planes and is obviously orthorhombic in chains. In total it is orthorhombic, so that the orthorhombic distortions persist in planes as well. They do not effect much lattice constants, but can be much more substantial for electronic properties. If they are not too large, they do not remove the nodes, but shifted them in tetragonally asymmetric positions. As a result $\langle \Delta \rangle \neq 0$. We show that such a picture can reconcile all the experimental data.

Consider two simplified models. In the first one we assume the Fermi-surface to be a circular cylinder, and $\Delta$ to depend on the azimuthal angle $\phi$ only: $\Delta(\phi) = \text{const}(\cos 2\phi + \gamma)$, where $\gamma$ is a constant. Then $\langle \Delta \rangle = \gamma$, and $\kappa = \langle \Delta^2 \rangle / \langle \Delta \rangle^2 = 1 + 1/2\gamma^2$. In the second model the Fermi surface is a square-shaped cylinder with the diagonals of square along $a$ and $b$-axes, and $\Delta(k) = (\cos k_x - \cos k_y) + \gamma$. Then again $\langle \Delta \rangle = \gamma$ and $\langle \Delta^2 \rangle = 2 + \gamma^2$. For the value $\kappa$ in this case we get: $\kappa = 1 + 2/\gamma^2$. From the measurements of $T_c$ vs $\rho$ [13], [14] we determine $\kappa = 2.0 \pm 0.3$, and $\gamma = 0.7 \pm 0.2$ for the circular geometry, and $\gamma = 1.4 \pm 0.2$. 
for the square-shaped Fermi-surface. Thus, the mixture of s-wave can not be small. For example, $\gamma = 0.3$ in the circular case gives $\kappa - 1 = 4.5$ inconsistent with the experiment. The non-zero average $\langle \Delta \rangle$ explains the non-zero tunneling observed in the experiment [1].

It is obviously smaller than it could be expected for an isotropic superconductor with $\Delta^2$ equal to $\langle \Delta^2 \rangle$ in the anisotropic superconductor.

We see that all the experiments can be reasonably described with this simple scheme. To make a choice between two above described models we consider the experiment by Dolan et al. [20]. They observed the anisotropy of the vortex lattice in the $a-b$-plane by the decoration method. The orthorhombicity is reflected in the Ginsburg-Landau tensor of effective masses, which is not isotropic in the orthorhombic symmetry. We have found the ratio of two eigenvalues of effective mass tensor:

$$\frac{m_x}{m_y} = \frac{\int v_x^2 \Delta^2(k) dS/v_F}{\int v_y^2 \Delta^2(k) dS/v_F}$$

where $v_x$ and $v_y$ are components of velocity, and integration proceeds over the Fermi-surface. For the circular model $v_x = v_F \cos \phi$, $v_y = v_F \sin \phi$. The integration in (1) is straightforward with the following result:

$$\frac{m_x}{m_y} = \frac{\gamma^2 + \gamma + 1/2}{\gamma^2 - \gamma + 1/2}$$

At $\gamma = 0.7$ this ratio takes its maximum value $\sim 5.9$. It means that the ratio of periods in the Abrikosov vortex lattice for the magnetic field along the $z$-axis should be $\sqrt{m_x/m_y} \approx 2.4$ not far from the transition temperature. Dolan et al. [20] have found for this ratio an estimate $\sqrt{m_x/m_y} \approx 1.15$, which is obviously incompatible with our estimate [1]. For the square-shaped Fermi-surface (1) gives the mass ratio equal to one exactly, since $v_x^2 = v_y^2$ on each side of the square. Therefore, experiments measuring $T_c(\rho)$ and anisotropy of effective mass together indicate implicitly that the shape of the Fermi-surface is close to a square or rectangle. We do not know a reliable experiment measuring the Fermi-surface in YBCO. The ARPES measurements in BiSCCO [21], [22] displayed indeed the square-shaped Fermi-surface. The numerical calculations by Massida et al. [23] also display this feature.
An interesting prediction which can be done from the value $\gamma = 1.4$ found earlier is that the nodes of the order parameter are located not exactly along the bisector between $a$ and $b$-direction, but they are shifted approximately halfway to one of these axes. Since BiSCCO and TlBaCaCuO has tetragonal symmetry it would be very important to perform tunneling experiments and measurements of $T_c$ supression by disorder to check whether the pure d-paring can consistently describe all the facts. It is interesting to note that the measurements of the transverse magnetization in LuBaCuO \[23\] with the same symmetry as YBCO displayed no nodes in the energy gap. In our language it simply means that $\gamma > 2$.

The experiment which still was not discussed in literature in connection with $s-d$ controversy is the plasma resonance. It has been found in YBCO by Koch \textit{et al.} \[25\] and in LaSrBaCuO by Tamasaku \textit{et al.} \[26\]. They observed a sharp decrease of reflectivity at the plasma frequency $\Omega_{pl}$ in superconducting state only. A theoretical analysis \[27\], \[28\] shows that it possible if $\Omega_{pl}\tau < 1$. In both materials $\Omega_{pl}$ was slightly more than $T_{c0}$, the transition temperature for clean superconductors. It means that definitely $\tau T_c < 1$. Such a superconductor is at least not too clean. Therefore, the energy gap in it should be presumably isotropic in controversy to the rest of experiments. In a quite recent experiments by Harris \textit{et al.} \[29\] the measurement of the Hall angle have been employed to demonstrate that for 60K YBCO the value $\tau$ is about 2 ps, which gives $T_c\tau \approx 16$. Besides of that, if there is no gap in the spectrum of excitations the Cooper pair breaking is allowed kinematically at any frequency, and one must expect a strong plasma waves attenuation in the superconducting state as well. This effect can be supressed dynamically in clean superconductors \[27\].

Steve Kivelson kindly informed me that the idea of reconciling the experimental data with orthorombic symmetry of YBCO has been launched by V.Emery and by himself \[30\]. I greatly benefited discussing this idea with V.Emery. Sharing the same general idea my work differs substantially with the scope of details. I am indebted to H.Monien and J.Blatter for indicating me several references and discussion.
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** When this work has been completed a microwave measurement by K.Zhang et al. [31] has been published, in which the authors have found for the same ratio 1.6. Though bigger than in the experiment [20], this ratio is still closer to the square-shaped model value, than to the circular one. The reason for the discrepancy in these two experiments is not clear.

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