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EFFECT OF IMPURITY SCATTERING ON THE MAGNETIC FIELD PENETRATION DEPTH IN $YBa_2Cu_3O_{7-\delta}$: COMPARISON WITH EXPERIMENTS

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Temperature dependence of the anisotropic magnetic field penetration depth of a two-band superconductor is calculated in the model of strong s-wave pairing interaction in one of the bands (S-band) and induced superconductivity in the second band (N-band). The results of the calculations are compared with experimental data on the ab-plane and c-axis penetration depth in $YBa_2Cu_3O_{7-\delta}$. It is shown that all recent measurements in the entire temperature range are consistent with the two-band model.

1. It is well known that electromagnetic properties of YBaCuO are not described by the standard weak coupling BCS model. In particular, the measurements of the temperature dependences of the magnetic field penetration depth $\lambda(T)$ have revealed an increased slope of $\lambda^{-2}(T)$ near the critical temperature T_c and nonexponential behavior of $\lambda(T)$ at $T < T_c/2$. These deviations could be, in principle, explained in terms of the model of strong electron-phonon interaction with isotropic superconducting order parameter. However, the results of microwave measurements of $\lambda(T)$ [1-3] obtained on higher quality YBaCuO samples cannot be described by this model. According to Ref. [1-3], the temperature dependence of $\Delta\lambda_{ab}(T)$ in ab-plane at $T < T_c/4$ changes from the exponential [3] to linear [1] and then to quadratic dependence [2] mainly with an increase of oxygen deficit in a sample. Subsequent microwave measurements [4,5] have confirmed the odd linear low-temperature behavior of $\Delta\lambda_{ab}(T)$. The inset to Fig.1 shows a low temperature part of the experimental $\Delta\lambda_{ab}(T)$ curve from Ref. [6]. Strong deviations from the isotropic BCS and strong-coupling models are seen in the figure.

The existence of crossover from the linear to quadratic temperature dependence of $\Delta\lambda(T)$ have been demonstrated by calculations made in the framework of d-wave pairing model with account taken of impurity scattering [7]. Such a crossover has been really observed in Ref. [4] upon doping of YBaCuO samples with Zn or Ni. However, it is impossible to reconcile the d-wave model with activation exponential behavior of $\Delta\lambda_{ab}(T)$. Moreover, the experimentally measured slope of $\lambda_{ab}^{-2}(T)$ dependences near T_c is much larger than that predicted by this model [8]. The qualitative difference between the c-axis penetration depth $\lambda_c(T)$ behaviors predicted by d- and s-pairing models was also pointed out in Ref. [8]. Very recently the low temperature dependence of $\Delta\lambda_{ab}$ was calculated in the framework of s-wave two-band model [9] first proposed in Ref. [10]. It was shown in Ref. [9]

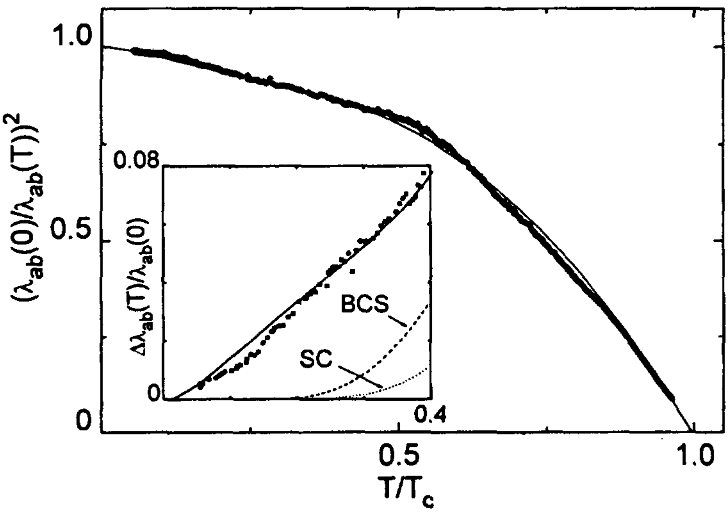

Fig.1. Plots of $\lambda_{ab}^{-2}(T)$ vs T/T_c. Solid labels: data from [6]. Solid line: 2-band model with $\gamma^s_{22} = 2.4$ meV, $\gamma_{12} = 0.8$ meV, $\gamma_{11} = \gamma_{22} = 32$ meV. Inset: Low T region of $\Delta\lambda_{ab}(T)$ vs T/T_c. Dashed: standard weak coupling BCS-model. Dotted: isotropic strong coupling model with $\lambda_{11} = 3$

that with increasing the concentration of magnetic impurities the crossover from the exponential to power law temperature dependence occurs.

Following this approach, the quantitative comparison between the calculations of $\lambda_{ab}(T)$ within the two-band model in the temperature range $0 < T < T_c$ and recent measurements in YBaCuO [3-6] is done in the present paper. We assume strong electron-phonon interaction in S-band (CuO_2-planes), while superconductivity in N-band (CuO-chains) is induced due to the interband proximity effect. We show that for temperatures not too close to T_c the value of $\Delta\lambda_{ab}(T)$ is mainly determined by both the intraband scattering on magnetic impurities in N-band and the usual scattering in N- and S-bands. Furthermore, good quantitative agreement is found between the calculations in the framework of two-band model and low-frequency measurements of the penetration depth $\lambda_c(T)$ on aligned ultrafine YBaCuO powders from Ref. [11]. The results of microwave measurements of the $\lambda(T)$ anisotropy in YBaCuO single crystals should be treated with care because (i) high precision adjustment of the sample position is necessary and (ii) the distribution of fields and currents in the sample is very complicated. Therefore we do not consider the microwave measurements of λ_c [5].

2. In the case of strong pairing interaction in S-band the Eliashberg strong-coupling theory is a starting point to discuss anisotropy effects, as it properly takes into account the effects of retardation and decay of quasiparticle excitations. The straightforward generalization of Eliashberg equations for the many-band case leads to the system of coupled equations:

$$\Delta'_{i,n}(i\omega_n) \equiv \Delta_{i.n} Z_{i,n} = \pi T \sum_j \sum_{n'} \{(\lambda_{ij} D_{n,n'} - \mu^*) + (\gamma_{ij} - \gamma^s_{ij})\} \frac{\Delta'_{j,m}}{\sqrt{(\Delta'_{j,m})^2 + (\omega'_{j,m})^2}}, \quad (1)$$

$$\omega'_{i,n}(i\omega_n) \equiv \omega_n Z_{i,n} = \omega_n + \pi T \sum_j \sum_{n'} \{\lambda_{ij} D_{n,n'} + (\gamma_{ij} + \gamma^s_{ij})\} \frac{\omega'_{j,m}}{\sqrt{(\Delta'_{j,m})^2 + (\omega'_{j,m})^2}}. \quad (2)$$

Here $D_{n,n'} = \sum_m \Omega_m^2 \left[(\omega_n - \omega_{n'})^2 + \Omega_m^2\right]^{-1}$ is the phonon Green function and Ω_m are phonon frequencies which we choose in the model form as $\Omega_1 = 200$ K,

$\Omega_2 = 5\Omega_1 = 10^3$ K. We note that the function $D_{n,n'}$ in Eqs. (1),(2) could stay for any other nonphonon interaction (except for spin interaction). Further, a particular choice of Ω_i does not change our conclusions because the coupling constants λ_{ij} are the most important parameters. The intraband coupling constants λ_{ii} describe the strength of electron-phonon interaction within i-th band. The physical meaning of interband coupling constants λ_{ij} $(i \neq j)$ is that they describe phonon mediated transitions between different bands. In the two-band case considered below this process leads effectively to the Cooper pair formation in N-band provided the coupling constant $\lambda_{21} \neq 0$. The terms γ_{ij} denote the scattering rates from band i into band j due to nonmagnetic impurities, and γ^s_{ij} are the magnetic scattering rates, $Z_{i,n}$ is a renormalization function, $\omega_n = \pi T(2n+1)$ are Matsubara frequencies. It is important to note that the interband scattering rates γ_{ij} $(i \neq j)$ lead to Cooper pair tunneling between the corresponding bands and therefore play the same role as λ_{ij} $(i \neq j)$ in the case of two bands N and S. For a weak coupling $\lambda_{ij} << 1$ Eqs.(1),(2) reduce to the equations of BCS model.

The choice of parameters of the model is motivated by the situation in YBaCuO. We assume that the planes are characterized by large coupling constant and form S-band ($\lambda_{11} = 3$), whereas the chains form N-band ($\lambda_{22} = 0$). A nonzero order parameter in the chains is induced through interband interactions $\lambda_{12} = \lambda_{21} = 0.2$. The above parameter set is consistent with $T_c \approx 90\,\mathrm{K}$ in YBaCuO.

We assume that the interband scattering rates γ_{ij} in Eqs.(1),(2) are small $\gamma_{12}, \gamma_{21} \ll T_c$ and we set $\gamma^s_{12} = \gamma^s_{21} = \gamma^s_{11} = 0$. Account is taken of the impurity scattering due to usual and magnetic impurities in N-band (γ_{22} and γ^s_{22}, respectively) and of the nonmagnetic scattering in S-band γ_{11}.

The origin of magnetic scattering is that upon decreasing the oxygen content the oxygen atoms move preferentially out of the chains. As a result, the chain Cu atoms develop magnetic moments which act as pair breakers. Thus, the magnetic scattering γ^s_{22} in N-band is the only free parameter of the model related to oxygen deficit in $YBa_2Cu_3O_{7-\delta}$.

The choice of elastic scattering rates in N- and S-bands should be made consistent with the absolute values and anisotropy of resistivities above T_c. The resistivity of the corresponding band (S, N) at T_c is estimated as

$$\rho_s(T_c) = 8\pi^2\hbar^{-1}\omega_{p,1}^{-2}k_BT_c\sum_i\left[\lambda^{tr}_{1i} + \frac{(\gamma_{1i}+\gamma^s_{1i})}{\pi k_BT_c}\right],$$

$$\rho_n(T_c) = 8\pi^2\hbar^{-1}\omega_{p,2}^{-2}k_BT_c\sum_i\left[\lambda^{tr}_{2i} + \frac{(\gamma_{2i}+\gamma^s_{2i})}{\pi k_BT_c}\right] \qquad (3)$$

where λ^{tr}_{ij} are transport coupling constants, $\omega_{p,1}$ and $\omega_{p,2}$ are the plasma frequencies of S- and N-band respectively. With plasma frequencies $3.6\,\mathrm{eV}$ for planes and $3.2\,\mathrm{eV}$ for chains [12] and the elastic scattering rates in N- and S-band $\gamma_{11} = \gamma_{22} = (2-4)T_c$ (16-32 meV) the model (1)-(3) is consistent with the absolute values of resistivity 50-100 $\mu\Omega$·cm at 100 K.

The electromagnetic response of a two-band superconductor can be calculated by generalization of the standard approach developed for strongly-coupled superconductors [9, 13]. The penetration depth in ab-plane is given by:

$$\frac{\lambda^{-2}_{ab}(T)}{\lambda^{-2}_{ab}(0)} = \frac{Q_1(T)+Q_2(T)}{Q_1(0)+Q_2(0)}, \qquad (4)$$

where the corresponding kernels for two bands are

$$Q_{1,2}(T) = \omega_{p;1,2}^2 \pi T \sum_{\omega_n=0}^{\infty} \frac{\Delta_{1,2}^2(i\omega_n)}{\left[\omega_n^2 + \Delta_{1,2}^2(i\omega_n)\right]^{3/2} Z_{1,2}(i\omega_n)}. \tag{5}$$

We assume that the conductivity in c-direction is nonmetallic [14], i.e. transport along c-direction occurs via incoherent hopping. In this limit the penetration depth λ_c is given by the Josephson interaction between neighboring pairs of planes and chains and is determined by

$$\frac{\lambda_c^{-2}(T)}{\lambda_c^{-2}(0)} = 8\gamma^* \frac{T}{T_c} \sum_{\omega_n=0}^{\infty} \frac{\Delta_1(i\omega_n)\Delta_2(i\omega_n)}{\sqrt{\omega_n^2 + \Delta_1^2(i\omega_n)}\sqrt{\omega_n^2 + \Delta_2^2(i\omega_n)}} \tag{6}$$

where $\gamma^* \simeq 1.78$ is Euler's constant.

3. With the parameters specified above, the Eliashberg equations are solved numerically for two bands. A set of $\lambda_{ab}^{-2}(T)$ curves for $\gamma_{22}^s = 1.6$ meV with different values of $\gamma_{11} = \gamma_{22}$ is shown in Fig.2. The single crystal data from Ref. [4, 5] ($\rho_{ab} \simeq 50\ \mu\Omega \cdot$ cm) are in a good agreement with the calculations except for temperatures close to T_c. The linear term at $T < 0.5T_c$ is well described by the model.

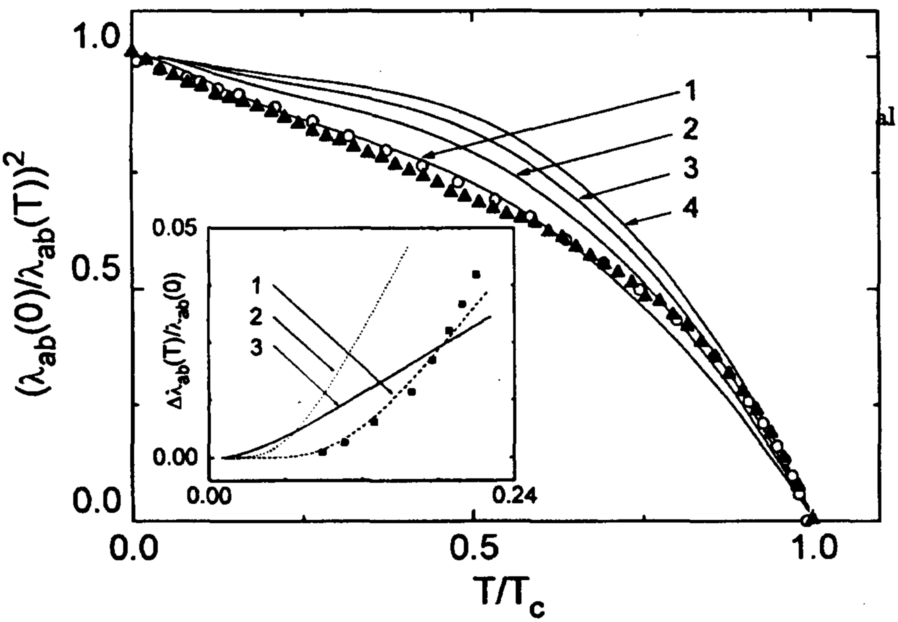

Fig.2. Calculated curves ($\gamma_{22}^s = 1.6$ meV, $\gamma_{12} = 0$) compared with data from Ref. [5] (triangles) and Ref. [4] (open circles). 1 - $\gamma_{22} = 16$ meV, 2 - $\gamma_{22} = 32$ meV, 3 - $\gamma_{22} = 64$ meV, 4 - $\gamma_{22} = 160$ meV. Inset: The crossover from exponential (curves 1,2) to linear (curve 3) behavior of $\Delta\lambda_{ab}(T)$ for $\gamma_{22} = 16$ meV and $\gamma_{22}^s = 0$ (1), 0.8 meV (2) and 3.2 meV (3). Solid squares: data from Ref. [3]

It was demonstrated explicitly in Ref. [15] that a small gap exists in N-band for $\gamma_{22}^s = 0$ and decreases rapidly with an increase of γ_{22}^s. As a result, at sufficiently large γ^s_{22} a gapless state develops in the system. Inset to Fig.2 displays the results of calculations of $\Delta\lambda_{ab}(T)$ for different γ^s_{22} values. As a consequence of the development of the gapless state the crossover takes place at low T from the exponential temperature dependence for $\gamma^s_{22} = 0$ to the linear temperature dependence at larger γ^s_{22}. The data of Ref. [3] are compared with our results for $\gamma^s_{22} = 0$. Good agreement between the theory and experiment points out that at low T the exponential temperature dependence can be attributed to the absence of magnetic impurities in fully oxygenated YBaCuO films [3].

With an increase of γ^s_{22} and γ_{22} the contribution of N-band to the penetration depth vanishes and the behavior of $\lambda_{ab}(T)$ becomes closer to that predicted by the isotropic strong-coupling model. Such a crossover illustrated in Figs.1 and 3 correlates well with the increase of the resistivity above T_c.

Fig.1 represents the quantitative comparison of the calculations of $\lambda^{-2}_{ab}(T)$ with the data on an electron-beam evaporated YBaCuO film [6]. The parameters $\gamma_{11} = \gamma_{22} = 32$ meV correspond to the experimental value of film resistivity $\rho_{ab} \simeq 80$ $\mu\Omega\cdot$cm at 100 K.

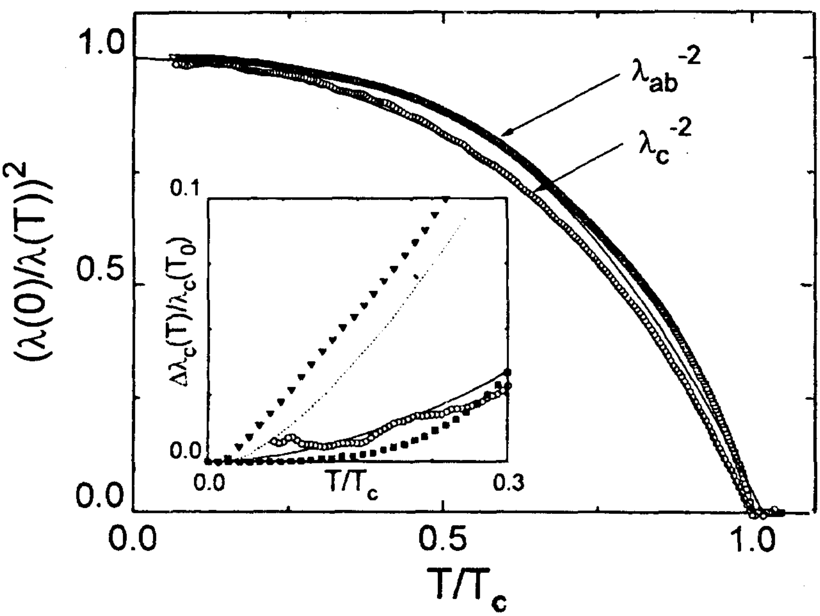

Fig.3. $\lambda^{-2}(T)$ vs T/T_c for $\lambda_c(T)$ and $\lambda_{ab}(T)$ from Ref. [11]. Solid: 2-band model with $\gamma^s_{22} = 6.4$ meV, $\gamma_{12} = 1.6$ meV, $\gamma_{22} = 24$ meV. Inset shows the results of 2-band model with $\gamma^s_{22} = 6.4$ meV, $\gamma_{12} = 1.6$ meV, $\gamma_{22} = 24$ meV (solid) and $\gamma^s_{22} = 1.6$ meV, $\gamma_{12} = 0$, $\gamma_{22} = 16$ meV (dotted). Open circles: low T part of the data Ref. [11]. $T_0 = 1.35$ K. Solid triangles: d-wave model from Ref. [8], solid squares: s-wave model from Ref. [8]

The computed $\lambda(T)$ curves alongside the data on YBaCuO powders [11] are shown in Fig.3. At low T the experimental dependence $\Delta\lambda^{-2}_{ab}(T) \sim T^2$ is in agreement with theory. A fit of the calculated $\lambda_c(T)$ curve to the experimental data [11] is presented in Fig.3. Our results for different sets of parameters γ^s_{22} and γ_{22} point to the absence of linear behavior of $\lambda_c(T)$, which is in contradiction to the predictions of d-wave model [7, 8].

So, the influence of impurity scattering on the magnetic field penetration depth in YBaCuO manifests itself in the following way. As discussed in Ref. [9 10], the magnetic scattering rate γ_{22}^{s} in N-band may serve as a quantitative measure of oxygen deficit in $YBa_2Cu_3O_{7-\delta}$. In fully oxygenated $YBa_2Cu_3O_7$ films [3] the magnetic pair-breaking in chains (N-band) is absent, i.e. $\gamma_{22}^{s} \simeq 0$. In this case the two-band model and measurements [3] demonstrate an exponential temperature dependence at low T with exponent given by a small proximity-induced energy gap in the chains. Even for relatively small concentration of magnetic impurities $\gamma_{22}^{s} \geq 0.2T_c$ a superconducting state in chains becomes gapless. The gaplessness results in a linear term in the contribution of chains to $\Delta\lambda_{ab}(T)$ at low T. The data of Ref. [4, 5] obtained in $YBa_2Cu_3O_{6.95}$ single crystals indeed shows a linear dependence of $\Delta\lambda_{ab}(T)$ in accordance with the model. When going from oxygen-deficient single crystals [4, 5] to oxygen-deficient $YBa_2Cu_3O_{7-\delta}$ thin films [6] and powders [11] the usual and magnetic scattering in the chains (γ_{22} and γ_{22}^{s}) increase. This leads to the suppression of the superconductivity in chains and to a decrease of chain contribution to the total penetration depth. As a result, the crossover at low T from the linear to quadratic [11] temperature dependence of $\Delta\lambda_{ab}$ takes place. This behavior correlates well with the experimental data corresponding to different values of resistivity above T_c.

In conclusion, we have demonstrated for the first time that all recent measurements of $\lambda_{ab}(T)$ in YBaCuO are consistent with the two-band model. The approach [9,10] for calculation $\lambda_{ab}(T)$ is extended to the entire temperature range $0 < T < T_c$ at arbitrary concentration of nonmagnetic impurities. The model correctly describes the disappearance of linear term in $\lambda_{ab}(T)$ with increasing sample resistivity. Temperature dependence of λ_c is calculated within the two-band model in the approximation of Josephson interaction between the layers. In this approach the linear term never appears in $\lambda_c(T)$ at low T. The key experiments to check the two-band description for YBaCuO would be measurements of $\lambda_c(T)$ on YBaCuO single crystals as well as those of $\lambda_{ab}(T)$ in oxygen depleted and Fe- or Ga-doped YBaCuO, when superconductivity of CuO chains is destroyed.

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1. W.N.Hardy, D.A.Bonn, D.C.Morgan et al., Phys. Rev. Lett. **70**, 3999 (1993).
2. Z.Ma, R.C.Taber, L.W.Lombardo et al., Phys. Rev. Lett. **71** , 781 (1993).
3. N.Klein, N.Tellmann, H.Schulz et al., Phys. Rev. Lett. **71**, 3355 (1993).
4. D.A.Bonn, S.Kamal, Kuan Zhang et al., Phys. Rev. B **50**, 4051 (1994).
5. Jian Mao, D.H.Wu, J.L.Peng et al., Phys. Rev. B **51** , 3316 (1995).
6. S.Orbach-Werbig, A.A.Golubov, S.Hensen et al., Physica C **235-240**, 1823 (1994).
7. P.J.Hirschfeld, W.O.Puttika, and D.J.Scalapino, Phys. Rev. B **50**, 10250 (1994).
8. R.A.Klemm and S.H.Liu, Phys.Rev.Lett. **74**, 2343 (1995).
9. S.D.Adrian, M.E.Reeves, S.A.Wolf, and V.Z.Kresin, Phys. Rev. B **51**, 6800 (1995).
10. V.Z.Kresin and S.A.Wolf, Phys. Rev. B **46**, 6458 (1992); **51**, 1229 (1995).
11. A.M.Neminskii and P.N.Nikolaev, Physica C **212** , 389 (1993).
12. I.I.Mazin and O.V.Dolgov, Phys.Rev.B **45**, 2509 (1992).
13. S.B.Nam, Phys. Rev. **156**, 487 (1967).
14. D.G.Clarke, S.P.Strong, and P.W.Anderson, Phys. Rev. Lett. **74**, 4499 (1995).
15. A.A.Golubov, O.V.Dolgov, E.G.Maksimov et al., Physica C **235-240**, 2383 (1994).