Effect of the pseudogap on the mean-field magnetic penetration depth of $YBa_2Cu_3O_{7-\delta}$ thin films

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We report measurements of the *ab*-plane penetration depth, $\lambda(T)$, in $YBa_2Cu_3O_{7-\delta}$ films at various δ. At optimal doping, critical fluctuation effects are absent, and $1/\lambda^2(T)$ from 4 K to 0.99 T_C is that of a clean, strong-coupling d-wave superconductor with $\Delta_0(0)/k_BT_C \simeq 3.3$. As in crystals, underdoping reduces the superfluid density, $n_s(0) \propto 1/\lambda^2(0)$, without affecting the low-T slope of $1/\lambda^2(T)$. These results, as well as electronic heat capacity data, are well described by an *ad hoc* model in which contributions to the superfluid and entropy are lost from regions of the Fermi surface occupied by the pseudogap.

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A large body of experimental evidence indicates the opening of a **k**-dependent gap, or pseudogap, at a temperature, T^*, above the superconducting transition temperature, T_C, in underdoped cuprates [1]. The pseudogap competes with the superconducting gap: T^* and the fraction of the Fermi surface (FS) occupied by the pseudogap increase with underdoping, while T_C, the superfluid density in the *ab*-plane, $n_S(0)$, and the peak value of the electronic specific heat coefficient, $\gamma(T)$, at T_C decrease. A great deal of effort currently focuses on understanding the coexistence of these two gaps. Lee and coworkers propose that the fundamental physics lies in spin-charge separation, a key element being the segmentation of the FS into regions either occupied or unoccupied by the pseudogap in the normal state [2]. With this in mind, we construct a simple model to describe our measurements of $n_S(T)$ and literature results for $\gamma(T)$, in which only portions of the FS unoccupied by the pseudogap contribute to the superfluid and entropy in the superconducting state.

We present new measurements of $1/\lambda^2(T) \propto n_S(T)$ in $YBa_2Cu_3O_{7-\delta}$ (YBCO) films at various δ. We show that $1/\lambda^2(T)$ in optimally-doped films is that of a clean, strong-coupling d-wave superconductor with a full FS. Underdoped films are well described by a Fermi liquid-like model, in which electronic properties are expressed as integrals over the FS, but the integrals extend only over sections of the FS not occupied by the pseudogap in the normal state. The fraction of the FS that survives is equal to the ratio of $n_S(0)$ of the underdoped film to $n_{S,opt.}(0)$ of the same film at optimal doping.

The absence of critical fluctuations in optimally-doped YBCO films [3] and measurements of the effect of thermal phase fluctuations on 2D films of a conventional superconductor [4] lead us to conclude that fluctuation effects are weak in the underdoped films. However, the relative importance of thermal phase fluctuations (TPF's) to single particle excitations is controversial. Carlson et al. [5] have shown numerically that a fluctuation driven superfluid density in Josephson junction (JJ) arrays displays features similar to some very clean YBCO crystals, namely, T-linear behavior at low-T [6], T_C roughly proportional to $n_S(0)$, and a wide critical region [7,8]. Terahertz measurements of the sheet conductance of BSCCO films also suggest a wide fluctuation region [9]. On the other hand, theoretical analyses of TPF's in underdoped cuprates conclude that fluctuations are too weak at low-T to account for the T-linear behavior of $\lambda(T)$ [10,11]. Consistent with these results, our estimates indicate that the effects of TPF's are minor.

It is not known why fluctuation effects near T_C are weak in optimally-doped YBCO films [3] and some crystals [12], while appearing strong in other crystals [7,8]. Films are of high quality, based on their T-linear $\lambda(T)$ at low-T and transition widths less than 1 K. Evidently, critical fluctuations are sensitive to structural differences which affect neither of these quality indicators. An estimate of the coupling between CuO bilayers in optimally-doped YBCO [13] finds that for T within 5 K of T_C, the ratio of interlayer coupling to in-plane coupling (J'/J in ref. [5]) is greater than unity and fluctuations should be strongly suppressed. To us, the presence of critical fluctuations in crystals is surprising, but their absence in films is not. We speculate that a significant portion of what appear to be critical fluctuations in crystals is, in fact, due to the rapid decrease in the quasiparticle scattering rate as T decreases below T_C [14] which serves to rapidly increase the conductivity, $\sigma_1(\omega, T)$, for ω less than the gap frequency, $\Delta_0(T)/\hbar$, thereby increasing n_S [15]. The decrease in scattering rate is known to be less rapid in disordered samples [16].

The d-wave theory which we use is an extension of the weak-coupling result for $\lambda^2(0)/\lambda^2(T/T_{C0})$ [17] to strong coupling by increasing the ratio $\Delta_0(0)/k_BT_{C0}$ above its weak-coupling value of 2.14, while preserving the dependence of $\Delta_0(T/T_{C0})/\Delta_0(0)$ on T/T_{C0}. T_{C0} is the mean-field transition temperature. $1/\lambda^2(T)$ and $\gamma(T)$ are determined from the usual FS integrals over **k**-space and energy.

For simplicity, we neglect possible deviations of $\Delta(\mathbf{k}, T)$ from $\Delta_0(T)\cos(2\phi)$ which are reported in ARPES measurements on underdoped $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ (BSCCO) [18] and which may or may not be present in YBCO. Possible anomalous behavior of the quasi-1D CuO chains [19] is not included. Because such behavior is not observed in untwinned crystals, it is likely that chain specific effects are negligible in our highly twinned films. Variation of the Fermi velocity, $v_F(\mathbf{k})$, with $\mathbf{k}$ is not included. If $n_S(0)$ is a factor F smaller than in the optimally-doped film, then FS integrals are taken only over the angular interval, $\pm F(\pi/4)$, centered at each node in $\Delta(\mathbf{k},T)$.

2D TPF's are predicted to suppress $n_S(T)$ [20] by a factor: $af_Q(T)k_BT\mu_0\lambda_\perp(T)/\hbar R_Q$. $1/\lambda_\perp(T) \equiv d/\lambda^2(T)$; $d = 11.7$ Å for YBCO. The prefactor, a, is not well known theoretically. We use $a = 0.175$ which is consistent with measurements on a-MoGe films [4] and calculations for a hexagonal array of resistively shunted JJ's [11,21]. $R_Q \equiv \hbar/4e^2 \sim 1027\ \Omega$ and f_Q $(0 \le f_Q \le 1)$ represents quantum suppression of TPF's. The 2D transition, T_{2D}, is expected where $\lambda_\perp(T_{2D})T_{2D} \simeq \pi\hbar R_Q/2k_B$ = 9.8 mmK. Since T_{2D} is near T_C, this condition is approximately $\lambda_\perp(T_{2D}) \simeq 9.8$ mmK$/T_C$. (In the absence of quantum effects, T_{2D} is the Kosterlitz-Thouless-Berezinskii transition temperature T_{KTB}.) As T approaches T_{2D}, the suppression of $n_S(T)$ grows rapidly due to nonlinear effects, reaching 20% to 50% just below T_{2D}.

Quantum suppression of TPF's in films has been controversial for some time. Recently, quantum effects were predicted [11] and observed [4] to suppress TPF's when $k_BT/\hbar$ drops below the "R/L" frequency of the film. Approximately, the sheet inductance is $L = \mu_0\lambda_\perp(T)$ and the sheet conductance is $1/R = \sigma_1(\omega \lesssim \Delta_0/\hbar, T)d$. For optimally-doped YBCO, f_Q should be much less than unity below 0.8 T_C.

Data presented here for films grown by coevaporation and sputtering are representative of other high quality films. Films allow the rapid and reversible adjustment of oxygen content without altering the thickness or microstructure of the film. The coevaporated YBCO films were grown using the BaF_2 method [22] with a room temperature $SrTiO_3$ substrate in an atmosphere of about 5×10^{-6} torr of O_2, with a postanneal in wet oxygen. After careful refinement of the growth rates from measurements of film stoichiometry by Rutherford Backscattering, YBCO films grown by this method consistently display a linear low-T penetration depth. Additional films made by RF sputtering and by *in-situ* coevaporation of Sm, Ba, and Cu [23] onto substrates held at 750 C to 800 C are presented. Optimally-doped film transition widths were less than 1 K, based on the peak in the real conductivity $\sigma_1(T)$. One of the codeposited YBCO films was deoxygenated three times to $\sim O_{6.8}$, $O_{6.7}$, and $O_{6.6}$ (determined from T_C) using low temperature anneals in argon.

The complex conductivity, $\sigma = \sigma_1 - i\sigma_2$, is determined from the mutual inductance of coaxial coils driven at 50 kHz located on opposite sides of the film [24]. With a well defined coil geometry and known film thickness, s, Maxwell's equations provide σ as a function of the

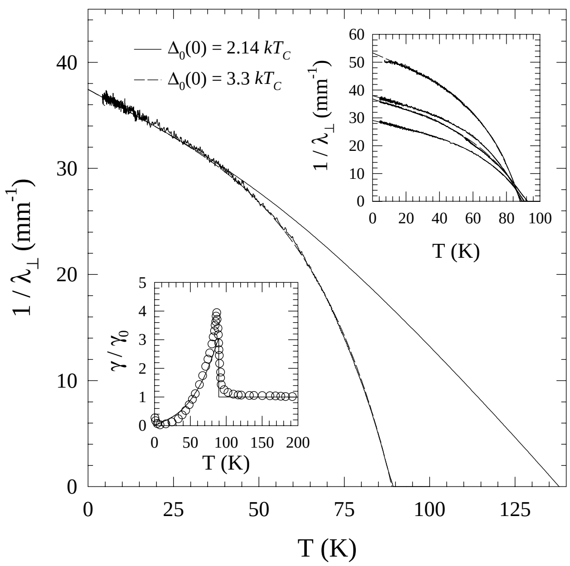

FIG. 1. The inverse of the 2D magnetic penetration depth ($1/\lambda_\perp = d/\lambda^2 \propto n_s$) for a YBCO film is shown with best low-T fits using a weak coupling gap $\Delta_0(0) = 2.14\ k_BT_C$ (solid line) and strong coupling gap $\Delta_0(0) = 3.32\ k_BT_C$ (dashed line). The data and the strong coupling fit are nearly indistinguishable. The upper right inset shows four additional films with strong coupling mean-field fits $\Delta_0(0) = 3.2 \pm 0.2 k_BT_C$ (dashed lines). The lower left inset compares the normalized electronic specific heat coefficient from Loram *et al.* [27] (open circles) with the d-wave result for $\Delta_0(0) = 3.32\ k_BT_C$ (solid line).

measured mutual inductance. Great care is taken to ensure that measurements are made in the linear response regime to within 0.1 K of T_C by taking successive measurements at increasingly smaller drive coil currents. σ_1 is very much smaller than σ_2 everywhere except very close to T_C. From σ_2 we define $\lambda_\perp$:

$$\lambda_\perp(T) \equiv \frac{s/d}{\mu_0\sigma_2\omega}. \quad (1)$$

While $\lambda_\perp(0)$ is determined to an accuracy of about 10%, limited by uncertainty in film thickness, relative changes induced by deoxygenation are known to better than 5%.

Figure 1 shows $1/\lambda_\perp(T)$ for an optimally-doped YBCO film. The solid curve is weak-coupling d-wave theory ($\Delta_0(0)/k_BT_{C0} = 2.14$) fitted to the low-$T$ data by adjusting T_{C0}. The dashed curve, which is nearly indistinguishable from the data, is strong-coupling d-wave theory with $\Delta_0(0)/k_B = 3.3\ T_{C0} \simeq 300$ K, consistent with tunneling measurements [25]. The upper right inset to Figure 1 shows the excellent agreement between the measured $1/\lambda_\perp(T)$ and mean-field curves for several optimally-doped YBCO films and one film of $SmBa_2Cu_3O_{7-\delta}$. Given $1/\lambda_\perp(0)$ and taking $v_F = 0.7 \times 10^5$ m/s [26], $\gamma(T)$ calculated with the same gap compares well with data [27] on bulk YBCO (lower left inset to Fig. 1, with $\gamma_0 = 16$ mJ/mole K^2). The small experi-

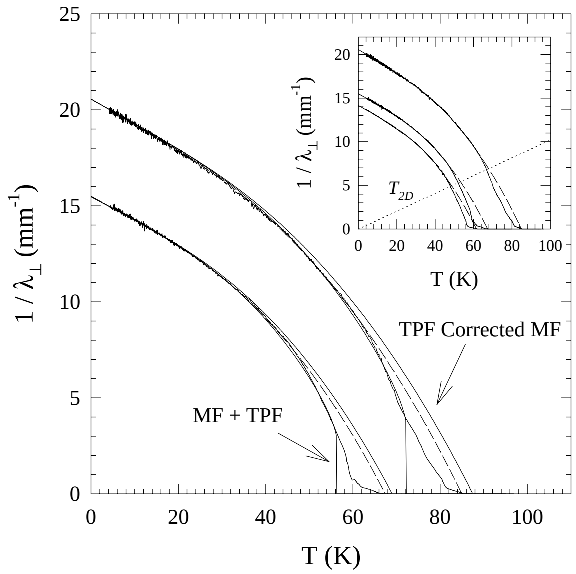

FIG. 2. The inset shows data for a coevaporated YBCO film at 3 stages of oxygen depletion, each successive stage having a lower $1/\lambda_\perp(0)$. Best low-T extrapolations are given by $\Delta_0(0) \simeq 2.5\ k_B T_C$ and are shown as dashed lines. The intersection between the data and the dotted line is where the classical 2D phase fluctuation transition would occur for completely decoupled layers. The main figure displays the data from the first two deoxygenation steps and fits incorporating 2D phase fluctuations (MF+TPF) which show a discontinuous drop at T_{2D}. The upper solid line are the corresponding curves with fluctuation effects removed (TPF Corrected MF).

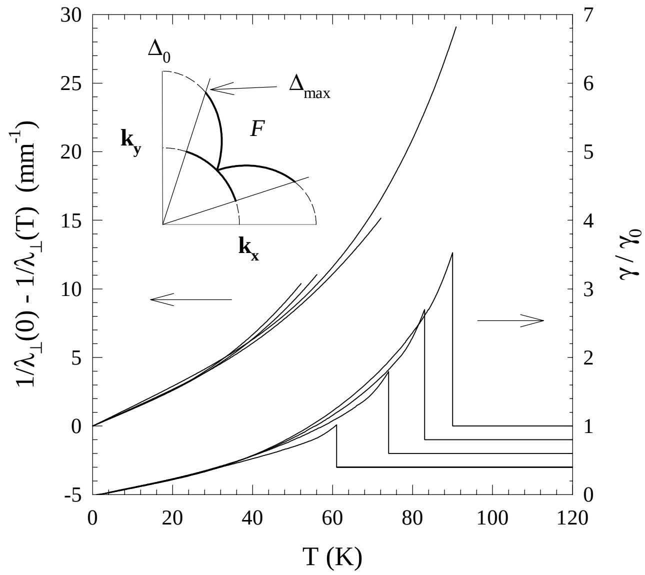

FIG. 3. $n_N(T) \propto 1/\lambda_\perp(0) - 1/\lambda_\perp(T)$ data for a YBCO film at optimal and 3 underdoped stages are shown. The data are truncated above T_{2D}. To the right are the calculated normalized electronic specific heat coefficients for F=1, 0.8, 0.6, and 0.4 (from highest peak to lowest peak). **k**-space integrals in the model, are taken only over a fraction of the Fermi surface, F, as illustrated in the inset.

mental $\gamma(T)$ at low-T could be fit better if the model allowed a **k**-dependent v_F and deviations of $\Delta(\mathbf{k})$ from $\cos(2\phi)$.

The inset to Figure 2 shows $1/\lambda_\perp(T)$ for a YBCO film at three stages of deoxygenation. It is striking that $\partial n_S(T)/\partial T$ at low-T (not necessarily the normalized shape) is essentially independent of doping despite the introduction of oxygen vacancies into the CuO chains. In our model, the unchanged slope, $d\lambda_\perp^{-1}(T)/dT|_{T\to 0}$, indicates no change in the opening of the gap near the gap nodes [28]. The downward curvature of $1/\lambda_\perp(T)$ reflects that of $\Delta_0(T)$ if TPF's are negligible. We wish to extract the underlying mean-field behavior by estimating the effect of 2D TPF's. For reference, the intersection of the dotted line with $1/\lambda_\perp(T)$ (inset to Figure 2) would locate T_{2D} were there no interlayer coupling and no quantum suppression of phase fluctuations.

The dashed curves in the inset and main portion of Figure 2 are extrapolations of the data taken below T_{2D}. The lower solid curves are fits in which hypothetical mean-field behavior (upper solid curves) is suppressed by TPF's. Since the influence of TPF's is determined by T, the normal-state sheet resistance, and $\lambda_\perp(T)$, all measured quantities, the only fitting parameter is T_{C0}. The third deoxygenation step yields fits similar to the first two, but is left out for clarity. A reduction in fluctuations as a result of interlayer coupling would bring the fluctuation-corrected mean-field result closer to the data, so uncertainty in mean-field behavior is bracketed by the upper solid curves and the data. We take the simple extrapolations (dashed curves) as reasonable approximations to mean-field behavior at least for $T < T_{2D}$. Our conclusions are insensitive to the extrapolation and to the "foot" seen just below T_C which is likely due to oxygen inhomogeneity.

Figure 3 displays the normal fluid density, $n_N(T) \propto 1/\lambda_\perp(0) - 1/\lambda_\perp(T)$, represented by the mean-field (dashed) curves of Fig. 2. Our model reproduces these when $\Delta_0(0) \simeq 300K$ is fixed and $T_{C0} \simeq F^{2/5}$, where $F \equiv n_S(0)/n_{S,opt.}(0)$ in the experimental range, $0.4 \leq F \leq 1$. The gap ratio, $\Delta_0(0)/k_B T_{C0}$, increases with underdoping, but the gap ratio defined from the maximum gap on the contributing FS segments, $\Delta_{max} = \Delta_0(0) cos(\frac{\pi}{2}(1 - F))$, increases only slightly. The contributing FS segments and Δ_{max} are shown pictorially in the inset to Figure 3.

The model provides a basis for interpretation of $\gamma(T)$ [27]. For optimal and mildly underdoped YBCO, there are three striking features in the data. One is that $\gamma(T)$ for $T \lesssim 60$ K is nearly independent of doping. Another is that the peak value of $\gamma(T)$ at T_C decreases much more rapidly than T_C with underdoping. Finally, the electronic entropy just above T_C, *i.e.*, the integral of $\gamma(T)$ from 0 K to T_C, decreases significantly. This implies that the hypothetical normal-state $\gamma(T)$ must decrease dramatically as T decreases below T_C, even though γ is nearly constant for $T > T_C$.

Figure 3 shows that $\gamma(T)$ calculated with parameters fixed by $\lambda(T)$ has all of the experimental features mentioned above. This is significant. Simple models which account for the reduction in $n_S(0)$ by an increase in the effective mass of electrons, for example, would not describe γ accurately. Our model incorrectly predicts that $\gamma(T)$ just above T_C should decrease with underdoping. We hypothesize that our model describes the electron degrees of freedom that condense into the superconducting state, and that there exists, in addition, an anomalous contribution to $\gamma(T)$ which arises from degrees of freedom not associated with the superfluid (perhaps from electron spin degrees of freedom) and which decreases rapidly in the vicinity of T_C.

For strong underdoping, $F \lesssim 0.4$, the model predicts that the thermodynamic critical field, $B_C(0)$, is proportional to $n_S(0)^{1/2}T_{C0}$, and the upper critical field, $B_{C2}(0)$, perpendicular to the ab-plane is proportional to T_{C0}^2 [29].

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