Effect of the pseudogap on the mean-field magnetic penetration depth of YBa$_2$Cu$_3$O$_{7-\delta}$ thin films

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(March 24, 2022)

We report measurements of the $ab$-plane penetration depth, $\lambda(T)$, in YBa$_2$Cu$_3$O$_{7-\delta}$ films at various $\delta$. At optimal doping, critical fluctuation effects are absent, and $1/\lambda^2(T)$ from 4 K to 0.99 $T_C$ is of a clean, strong-coupling d-wave superconductor with $\Delta_0(0)/k_BT_C \approx 3.3$. 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.

PACS Nos. 74.25.Fy, 74.25.Nf, 74.40.+k, 74.76.Bz

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$_2$Cu$_3$O$_{7-\delta}$ (YBCO) films at various $\delta$. 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-$T$. $T_C$ roughly proportional to $n_S(0)$, and a wide critical region [6]. Terahertz measurements of the sheet conductance of BSCCO films also suggest a wide fluctuation region [7]. 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 $\lambda(T)$ [8]. 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 and some crystals [9] and which may or may not be present in YBCO. Pos-
sible anomalous behavior of the quasi-1D CuO chains \[19\] is not included. Because such behavior is not observed in unwinned crystals, it is likely that chain specific effects are negligible in our highly twinned films. Variation of the Fermi velocity, \(v_F(k)\), with \(k\) 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 \(\Delta(k, T)\).

2D TPF’s are predicted to suppress \(n_S(T)\) \[22\] by a factor: \(a f_Q(T) k_B T \mu_0 \lambda(T)/\hbar R_Q\). \(1/\lambda(T) \equiv d/\lambda^2(T)\); \(d = 11.7\ \text{Å}\) for YBCO. The prefactor, \(a\), is not well known theoretically. We use \(a = 0.175\) which is consistent with measurements on \(\alpha\)-MoGe films \[4\] and calculations for a hexagonal array of resistively shunted JJ’s \[11,21\]. \(R_Q \equiv \hbar/4 e^2 \approx 1027\ \Omega\) and \(f_Q (0 \leq f_Q \leq 1)\) represents quantum suppression of TPF’s. The 2D transition, \(T_{2D}\), is expected where \(\lambda(T_{2D})T_{2D} \sim \pi \hbar R_Q/2k_B = 9.8\ \text{mmK}\). Since \(T_{2D}\) is near \(T_C\), this condition is approximately \(\lambda(T_{2D}) \approx 9.8\ \text{mmK}/T_C\). (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 \(k_B T/\hbar\) drops below the \(\nu R/L^2\) frequency of the film. Approximately, the sheet inductance is \(L = \mu_0 \lambda(T)\) and the sheet conductance is \(1/R = \sigma(\omega \lesssim \Delta/(\hbar, T))d\). 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 \[23\] with a room temperature SrTiO\(_3\) substrate in an atmosphere of about \(5 \times 10^{-6}\) 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 \(O_{6.8}, O_{6.7}, \text{and } O_{6.6}\) (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 \(\sigma\) as a function of the 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. \(\sigma_1\) is very much smaller than \(\sigma_2\) everywhere except very close to \(T_C\). From \(\sigma_2\) we define \(\lambda_\perp\):

\[
\lambda_\perp(T) \equiv \frac{s/d}{\mu_0 \sigma_2 \omega}.
\]

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 \((\Delta_0(0)/k_B T_C = 2.14)\) fitted to the low-\(T\) data by adjusting \(T_C\). The dashed curve, which is nearly indistinguishable from the data, is strong-coupling d-wave theory with \(\Delta_0(0)/k_B = 3.3\) \(T_C \approx 300\) K, consistent with tunneling measurements \[23\]. 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\(_2\)Cu\(_3\)O\(_{7-6}\). Given \(1/\lambda_\perp(0)\) and taking \(v_F = 0.7 \times 10^8\ \text{m/s}\) \[24\], \(\gamma(T)\) calculated with the same gap compares well with data \[27\] on bulk YBCO (lower left inset to Fig. 1, with \(\gamma_0 = 16\ \text{mJ/mole } K^2\)). The small experi-

![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 \(\Delta_0(0) = 2.14\ k_B T_C\) (solid line) and strong coupling gap \(\Delta_0(0) = 3.32\ k_B T_C\) (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 \(\Delta_0(0) = 3.2 \pm 0.2 k_B T_C\) (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 \(\Delta_0(0) = 3.32\ k_B T_C\) (solid line).]
Figure 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).

The inset to Figure 2 shows $1/\lambda_\perp(T)$ for a YBCO film at three stages of deoxygenation. It is striking that the peak value of $\gamma(T)$ at low-$T$ could be fit better if the model allowed a $k$-dependent $v_F$ and deviations of $\Delta(k)$ from $\cos(2\phi)$.

For optimal and mildly underdoped YBCO, there are three striking features in the data. One 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 $\gamma$ is nearly constant for $T > T_C$.

The third feature is the suppression of phase fluctuations. For reference, 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).
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 $\gamma$ 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 $n_{S}(0)^{1/2}T_{CD}$, and the upper critical field, $B_{C2}(0)$, perpendicular to the $ab$-plane is proportional to $T_{C}^{2}$.

The authors would like to thank Aaron A. Pesetski and John A. Skinta for useful discussions and James E. Baumgardner ii for numerical calculations and data analysis software. The SmBaCuO film was generously provided by Vladimir Matijasevic. This work was supported in part by DOE Contract No. DE-FG02-90ER45427 through the Midwest Superconductivity Consortium.

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