Low temperature vortex phase diagram of $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$: a magnetic penetration depth study

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We report measurements of the magnetic penetration depth $\lambda_m(T)$ in the presence of a DC magnetic field in optimally doped $BSCCO-2212$ single crystals. Warming, after magnetic field is applied to a zero-field cooled sample, results in a non-monotonic $\lambda_m(T)$, which does not coincide with a curve obtained upon field cooling, thus exhibiting a hysteretic behaviour. We discuss the possible relation of our results to the vortex decoupling, unbinding, and dimensional crossover.

1. INTRODUCTION

The field-temperature phase diagram of Bi-2212 is well studied at high and intermediate temperatures [1-5]. At low temperatures, the situation is less clear. Below $t=T/T_c=0.2$ the fishtail disappears, persistent current density increases almost exponentially (Fig.1), and the relaxation rate changes [2]. Theory predicts various peculiarities in vortex behavior at low temperatures, such as dimensional crossover in the pinning mechanism [2], topological transition in the vortex lattice [3,4], electromagnetic decoupling and a related Kosterlitz-Thouless type transition [5].

We present new experimental results on $\lambda_m(T)$ at low temperatures and discuss their relevance to the aforementioned scenarios.

2. EXPERIMENTAL

Magnetic penetration depth measurements were performed using a tunnel-diode driven $11$ MHz LC resonator [6] operating in a $^3$He refrigerator. The resonance frequency shift $\Delta f=f(T)-f(T_{m\text{r}})$ is related to $\Delta \lambda_m$ via $\Delta \lambda_m=-G \Delta f$, where $G$ is the sample and apparatus dependent calibration constant [7]. Magnetization was measured using a Quantum Design SQUID.

3. RESULTS

![Figure 1. Irreversible part of the magnetic moment in BSCCO at $H=300$ G. Inset: Log plot.](image)

Figure 1 presents the irreversible part of the magnetic moment, $M_{irr}=(M_1-M_1)/2$, as a func-
tion of temperature at \( H = 300 \text{ G} \). Here, \( M_{d} \) is the descending and \( M_{\uparrow} \) is the ascending branch of \( M(H) \) loop, respectively. The inset shows the same data in a log plot. Above certain temperature, \( T_{\text{irr}} \), \( M_{\text{irr}}(T) \) is exponentially suppressed indicating a weak pinning regime.

Figure 2. \( \Delta \lambda_{m}(T) \) at \( H = 300 \text{ G} \). Symbols and arrows are described in the text.

Figure 2 shows the magnetic penetration depth \( \Delta \lambda_{m}(T) \) measured at \( H = 300 \text{ G} \). The sample was cooled to \( T = 1 \text{ K} \) and magnetic field was applied (point 1 in Fig.2). The sample was then warmed up (1→2) and cooled down (2→3). Subsequent warming and cooling did not modify the temperature dependence of \( \lambda_{m}(T) \) – it always followed the “reversible” (3→2→3) curve. There are two distinctive points: \( T_{\text{dip}}(H) \) above which \( \lambda_{m}(T) \) is dominated by the reversible (3→2) curve; and \( T_{\text{irr}}(H) \) where reversible and irreversible curves merge. The observed hysteresis in \( \lambda_{m}(T) \) can be attributed to a crossover from a strong to a weak pinning regime, which is consistent with the measurements of the irreversible magnetization in Fig. 1.

We measured \( \lambda_{m}(T) \) at different values of the DC magnetic field and determined both \( T_{\text{dip}}(H) \) and \( T_{\text{irr}}(H) \). The resulting phase diagram is shown in Fig.3. The usual irreversibility temperature, \( T_{\text{irr}}(H) \), determined from the AC susceptibility measurements is also shown for comparison.

Unlike \( T_{\text{irr}}(H) \), neither \( T_{\text{dip}}(H) \) nor \( T_{\text{irr}}(H) \) extrapolate to \( T_{c} \) but at most to \( t = 0.5 \). This fact favors an unbinding transition scenario, in which the Kosterlitz - Thouless temperature sets the temperature scale [5].

Alternative mechanisms could be a dimensional crossover in the pinning mechanism [2] or a topological transition in the vortex structure [3,4]. We also note that the fishtail feature exists only between \( T_{\text{dip}} \) and \( T_{\text{irr}} \) lines, Fig.3, where the pinning is weak. This would imply a collective creep, dynamic explanation of the fishtail. However, a knee in \( T_{\text{irr}}(H) \) at \( H = 400 \text{ G} \) (onset of a fishtail) could be an indication of the entanglement crossover [4] in the vortex structure in this temperature region.

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REFERENCES

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