# Observation of sequence of transitions from 2D to 3D superconducting state in $YBa_2Cu_3O_{6+x}$ single crystal


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**Abstract**

Using the high-resolution SQUID magnetometer we have observed a sequence of narrow transitions from 2D to 3D superconducting state on $YBa_2Cu_3O_{6+x}$ single-crystals. The transitions clearly do not originate in vortex matter or non-homogeneous sample with multiple phases with varying $T_c$.



*Key words:* $YBa_2Cu_3O_7$; critical temperature; dimensional crossover; transition


Some related effects were already observed: (i) Krusin-Elbaum *et al.* using induction coil susceptometer operating at 1 MHz, with $\mu_0 H_{ac}$ typically 5 to 10 $\mu$T, tracked the peak position in temperature dependence of absorption (Im$\chi$)[1]. The sharp ($\Delta T \sim$20 mK) step was observed in the irreversibility line at about 1 K below $T_c$ at *dc* fields ($\mathbf{H}||c$) considerably above the lower critical field. This sudden irreversibility collapse, which depends on field orientation, was explained by thermal softening of the vortex core pining; (ii) Feigelman and Vinokur identified this transition as entangled vortex-liquid state (re-entrant boundary between entangled and lattice phases near $H_{c1}$)[2]; (iii) Safar *et al.* observed drop in $H_{c1}$, independent of the orientation of the field, anomaly in the relaxation of the remanent moment in field up to 35 mT. They found the vertical boundary in the $H-T$ plane, which was attributed to thermal decoupling of $CuO_2$ planes[3].

All the above experiments were done in dc field of the order of one Tesla. Our data were taken in dc field less than 1 $\mu$T, thus the vortex density is about six orders lower, but transition temperatures remain unchanged. We used the high resolution SQUID magnetometer with a noise level of the magnetic moment $|\mathbf{m}|\sim$100 fA m$^2$[4]. Since in our magnetometer the sample is static both with respect to the solenoid and detection system, the disturbing fields are very weak. The external field noise is below 1 nT. The high resolution allows observe details on sample magnetization, which are not smeared by external or applied field noise. The cooling or warming rate of the sample was 1 mK/s. The frequency of applied ac field was $f$ = 1.5625 Hz. The measurements shown in this paper were obtained on sample with dimensions in *ab* plane 0.29×1.7 mm$^2$ and thickness 35 $\mu$m. The observed signals prove an excellent sample quality since main absorption lines are narrow and magnetic properties at both orthogonal orientations have very small "cross-talk".

In $\mathbf{H}||c$ orientation, see Fig. 1: formation of superconductivity starts below $T_0$ = 92.2 K. The Re($m_{ac||}$) monotonously decreases with a sudden drop at $T_1$ = 91.2 K and much smaller drop at $T_2$ = 89.5 K. Just above $T_1$ the $m_{ac||}$ is about 30% of its zero temperature value and just below $T_1$ is 60% which represents sudden increase by $\sim$30% within 10 mK interval. The Im($m_{ac||}$) is constant and nonzero, has a high and sharp peak at $T_1$. Below $T_1$ absorption decreases linearly, with a smaller narrow peak at $T_2$. Below transition at $T_3$ = 87.1 K the absorption is zero.

In $\mathbf{H}\perp c$ orientation, see Fig. 2: formation of su-


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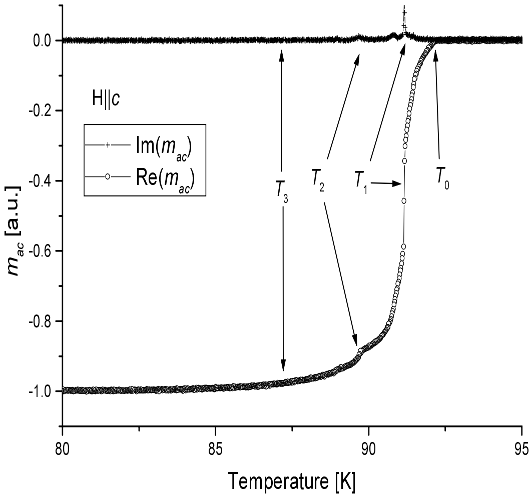


Fig. 1. The $m_{ac||}$ in H||c, $|\mu_0 H_{dc}| < 1$ $\mu$T, $\mu_0 H_{ac} = 1\mu$T.

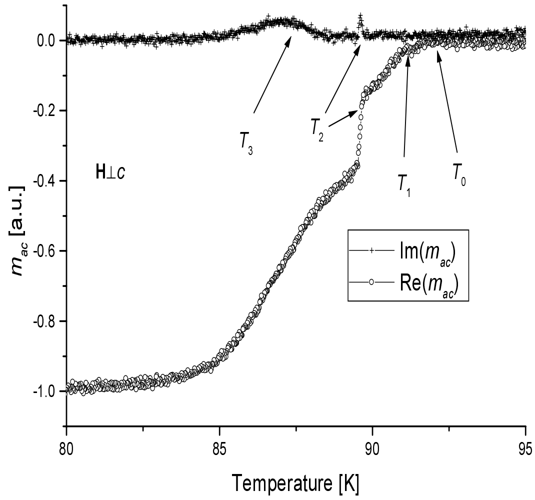


Fig. 2. The $m_{ac\perp}$ in H⊥c, $|\mu_0 H_{dc}| < 1$ $\mu$T, $\mu_0 H_{ac} = 1\mu$T.

perconductivity starts below 92.2 K. The Re($m_{ac\perp}$) monotonously decreases with a sudden drop at temperature $T_2$. This drop is only half of the low temperature value of the *ac* moment. The Im($m_{ac\perp}$) linearly decreases down to $T_1$ and becomes constant and nonzero below $T_1$. At temperature $T_2$ occurs a high and sharp absorption peak, followed by a wide peak at $T_3$. Below transition at $T_3$ the absorption is zero. Small increase of Re($m_{ac}$) at $T_2$ is seen in $\mathbf{H}||c$ but large in $\mathbf{H}\perp c$ where suddenly increases from ∼20% to ∼ 40% of its zero temperature value.

There is a remarkable symmetry of *ac* moments round transition temperatures $T_1$ and $T_2$. The zero temperature value of Re($m_{ac||}$)/Re($m_{ac\perp}$) = 12, which is close to the ratio of the sample cross sections estimated by optical microscopy, $S_{||}/S_{\perp} = 8.3$. Temperature dependencies of *ac* moments at cooling and warming are identical, without hysteresis. The half-width of absorption lines at $T_1$ and $T_2$ is only about 10 mK, whereas $T_1 = 0.99T_0$! At such a temperature one expects effects of broadening or smearing due to a thermal fluctuations. But the *ac* moment data are perfectly reproducible and without temperature hysteresis. The width of transitions at $T_1$ and $T_2$ rapidly increases with amplitude of the $H_{ac}$, while changes very little with $H_{dc}$ unlike transition at $T_3$. We performed measurements at $f/2$ and $2f$ but we did not observe any frequency dependence of *ac* or *dc* moments.

The observed transitions are not related to vortex lattice neither change of vortex dynamics nor decoupling of 3D vortex lines into 2D pane-cakes. The transitions reflect change of shielding currents - i.e. electric charge transport properties. The $T_1$ transition occurs in ab plane while $T_2$ and $T_3$ in *c*-axis direction. We suggest the following interpretation: $T_1$ transition shows appearance of 2D superconductivity in $CuO_2$ layers. Below $T_2$ the $CuO_2$–Y–$CuO_2$ sandwiches become superconducting. Above $T_2$ the Y layers are in normal state and this SNS sandwich becomes superconducting via proximity effect. On $m_{ac}$ in $\mathbf{H}||c$ this transition is masked by superconducting $CuO_2$ layers. Finally, at $T_3$ the $CuO_2$-Y-$CuO_2$ sandwiches become weakly coupled and the supercurrent is tunneling through the Ba-CuO-Ba barriers. At even lower temperature when this transition is completed the superconductivity is 3D.

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