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Signature of the matching field in Bose-glass melting of untwinned $YBa_2Cu_3O_{7-\delta}$ single crystals

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We map out the phase boundary separating the Bose-glass and vortex-liquid phases in an irradiated twin-free $YBa_2Cu_3O_{7-\delta}$ single crystal. We take the phase boundary to be the temperature T_g and magnetic field H at which the crystal begins to screen a small ac magnetic field, h_{ac}. There is a significant change in slope dT_g/dH of the phase boundary at the matching field B_Φ ($\simeq 0.5$ T) indicating that interstitial vortices significantly weaken pinning in the Bose-glass state. There is also a pronounced peak in the slope dT_g/dH just below B_Φ at higher h_{ac}. Both features disappear when the field is tilted away from the columns.
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Understanding the nature of the transition from vortex liquid to solid in the high-T_c cuprates has been a challenge because of the important role played by microscopic disorder.[1] Of particular interest is the case of correlated disorder produced by columnar defects. These defects, artificially created by the damage tracks from heavy ion irradiation, extend over large distances (μm) and pin vortices much more effectively than ordinary point defects. Nelson and Vinokur[2] (NV) have mapped the statistical mechanics of vortices in the presence of columnar defects onto that of two-dimensional bosons in a random potential. They show the existence of a Bose-glass phase where vortices become localized on columnar defects. This phase is characterized by an infinite tilt modulus and by a vanishing linear resistivity at the transition temperature. A unique situation occurs at the matching field, B_Φ, which is the magnetic field at which the number of vortices equals that of columnar defects. NV find that, at low temperatures, $B=B_\Phi$ coincides with a Mott insulator phase with infinite compressional modulus. Evidence for such a phase has been observed in recent experiments on magnetization relaxation.[3] The question we address here is to what extent B_Φ also marks a special point at higher temperatures, along the melting line for the Bose glass.

Experimental results so far, with the exception of Refs. 4 and 5, have not shown any evidence of characteristic changes in the melting line at B_Φ.[6–9] This state of affairs appears to support the original predictions by NV who found the phase boundary to be smooth through the matching field. However, there are several issues, both experimental and theoretical, that make the evidence less clear. They involve the effect of residual disorder from twinning or point defects and, in particular, the necessary degree of alignment between the magnetic field direction and the columnar defect axis. This becomes important in light of recent theoretical approaches[10,11] which have shown that the melting line should exhibit a characteristic, cusplike feature at B_Φ, i.e., a change of slope and curvature. In particular, it appears that this feature should persist in the experimentally important limit where the average defect spacing d is much less than the magnetic penetration depth λ and interactions involving many vortices become important.[10,11]

We address these issues in a systematic way by mapping out the melting line of the Bose-glass phase in an untwinned, ion-irradiated single-crystal of $YBa_2Cu_3O_{7-\delta}$, taking particular care with alignment and induced currents. We measure the Bose-glass transition temperature T_g as a function of magnetic-field component applied parallel to the columnar defect axis, $H_\parallel$, and find T_g highly sensitive to the perpendicular field components and to large ac driving field. In contrast to previous experiments,[6–9] we observe a 30% change in the slope of the melting line at the matching field. However, rather than the cusplike feature predicted by recent theories, we find a knee joining two nearly linear segments above and below B_Φ.

The untwinned $YBa_2Cu_3O_{7-\delta}$ crystal which we probed in most detail had a critical temperature T_c greater than 92.5 K. Its dimensions were $500\times500\times35$ μm^3 with the shortest dimension parallel to the c axis. The columnar defects were created by irradiation at Argonne's ATLAS source with 700 MeV Sn ions incident parallel to the c axis. The ion tracks produced amorphous cylinders of approximate diameter 70 Å. The radiation dose corresponded to a matching field $B_\Phi \simeq 0.5$ T.

The dc magnetic field H, applied along the crystal's c axis, was generated by a superconducting solenoid. Field components along the other, orthogonal directions were added with two shimming coils. We applied a small ac magnetic field h_{ac} (parallel to the c axis) to measure T_g, using a small copper coil. It generated a field in the range 0.2–18 G. A smaller multiturn coil resting flat against the crystal surface detected the screening currents in the sample via a lock-in amplifier. In the limit of linear response, the sample will screen the applied field when the skin depth is comparable to the sample dimension. At low frequencies (in our case $\simeq 1000$ Hz) this occurs as the resistivity approaches zero, i.e., as vortex motion ceases. While it is possible to define T_g as the maximum in the out-of-phase susceptibility, we chose the onset of screening to minimize the current density induced in the sample. At the lowest drive the current density at T_g was approximately 2 A/cm^2, and the 10%–90% transition width varied from 0.25–0.50 K depending on the magnetic-field strength. At larger drives the response be-

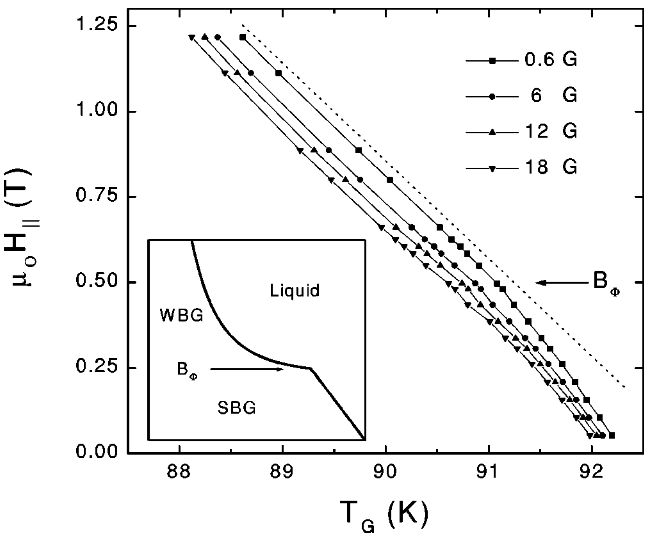

FIG. 1. Magnetic field $H_\|$ as a function of transition temperature T_g for excitation fields $\mu_0 h_{ac}$ of 0.6, 6, 12, and 18 G. There is a clear break in slope at the matching field B_Φ. Inset: Phase diagram derived from Ref. 10 showing the theoretical prediction for a strongly (SBG) and a weakly pinned vortex glass (WBG) below and above B_Φ, respectively.

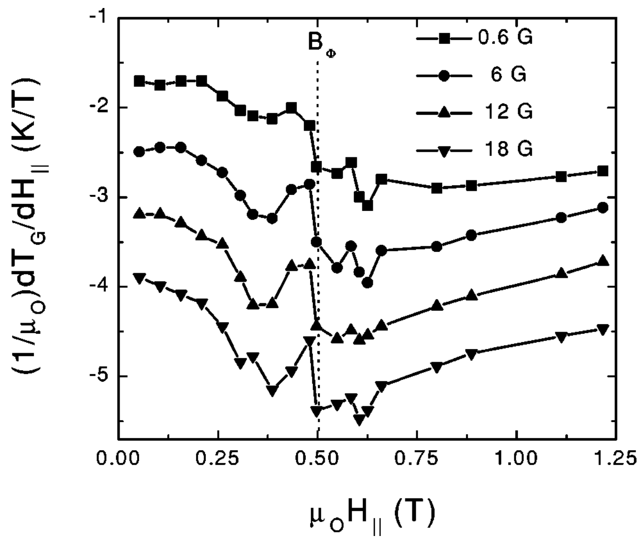

FIG. 2. $dT_g/dH_\|$ plotted against the applied magnetic field $\mu_0 H_\|$ at excitation fields $\mu_0 h_{ac}$ of 0.6, 6, 12, and 18. These data were calculated by discrete differentiation of the data in Fig. 1 and are offset for clarity.

came highly nonlinear, and the transition broadened to about 3 K. We took T_g as the temperature at which the screening signal reached 20% of its maximum value and verified that the shape of the melting line was insensitive to the choice of the threshold value. Given a sample aspect ratio of approximately 10 and a frequency of 1 kHz, our criterion corresponded to a resistivity ranging from 10^{-2}–10^{-3} $\mu\Omega$ cm, which is at least a factor 10^3 below the normal-state resistivity. With this technique, changes in T_g were detectable even when $H_\perp/|H|$ varied by as little as 10^{-3}. Due to this extreme sensitivity to the direction of H, we determined the proper, *three-dimensional* alignment at each temperature by adjusting the field orientation until T_g was maximized.

We show in Fig. 1 the melting line, $\mu_0 H_\|$ vs T_g, for several different values of the driving field h_{ac}. The most striking feature is a well-defined knee at $\mu_o H_\| = B_\Phi$. We find that this knee has moved to the highest T_g and is most pronounced for the weakest drive where the response to drive is linear. In addition, we find that the knee persists in measurements taken at a frequency of 100 kHz (which corresponds to larger resistive criterion for T_g). Thus, it is not an artifact of too large a measuring current, but it is intrinsic to the phase boundary (i.e., where $\rho \rightarrow 0$). Let us focus first on the low-drive melting line which corresponds to the linear response regime. In general, the decrease in slope of the melting line above the knee indicates that the vortex glass is more weakly pinned for $\mu_o H > B_\Phi$. Such a decrease is qualitatively consistent with the predictions of Refs. 10 and 11. In particular, Radzihovsky finds a strongly pinned Bose-glass (SBG) phase with a steep sloping boundary below the matching field, and above it a weakly pinned Bose glass (WBG) with very shallow slope. However, the precise shape of the experimentally determined melting line is very different from that of the available theory (inset to Fig. 1). Just above B_Φ theory predicts power-law behavior $(B - B_\Phi)^p$ as depicted in the inset, with exponents p of $\frac{1}{4}$ (Ref. 10) or $\frac{1}{6}$.[11]

We note that the theory in Ref. 10 was developed for the low-field limit ($B - B_\Phi \simeq \mu_0 H_{c_1}$ with $\mu_0 Hc_1 < 100$ G over the temperature range of the measurement), while Ref. 11 discusses a much larger range. In contrast to both predictions, our data does not exhibit a concave shape. Rather, we find that $T_g(H)$ varies in a simple linear fashion with H both below and above B_Φ.

We next discuss in more detail how both the strength of the ac excitation and the degree of field alignment affect the phase boundary. In the nonlinear regime of strong drive we are no longer sensing the actual glass temperature. However, T_g as we define it, remains a measure of vortex pinning strength. For increased drive, the data in Fig. 1 indicate that the melting lines become convex just above the matching field and concave below. The two curved segments do not meet to form a single inflection point at B_Φ. Instead, they are offset vertically. This is brought out more clearly by taking the derivative of the data, which we plot in Fig. 2. For $B > B_\Phi$, $dT_g/dH_\|$ is nearly constant for the lowest drive (as expected) and, at larger drives, all the curves are linear and have a similar positive slope. In fact, for $h_{ac} > 0.6$ G all the curves are remarkably similar. The knee in the melting line shows up (for $h_{ac} \simeq 0.6$ G) as a drop in the slope at B_Φ. This marked change in slope is most easily explained in terms of the balance between vortex and columnar defect densities. As soon as vortices begin to outnumber pinning sites, the maximum possible pinning force (or energy) decreases with increasing B. While one may have expected the change of slope to become smeared out as the knee disappears and the drive increases, we find instead that the jump in slope at B_Φ is robust.

Figure 2 also shows that a local minimum followed by a maximum in $dT_g/dH_\|$ develops just below B_Φ as the drive increases. The special role played by the matching field $B = B_\Phi$ is emphasized in the $T \rightarrow 0$ limit where an energy gap opens up in the distribution of pinning energies.[2] Although a hard energy gap is expected for short-range vortex-vortex interactions, Refs. 12–14 find that a soft Coulomb gap is still

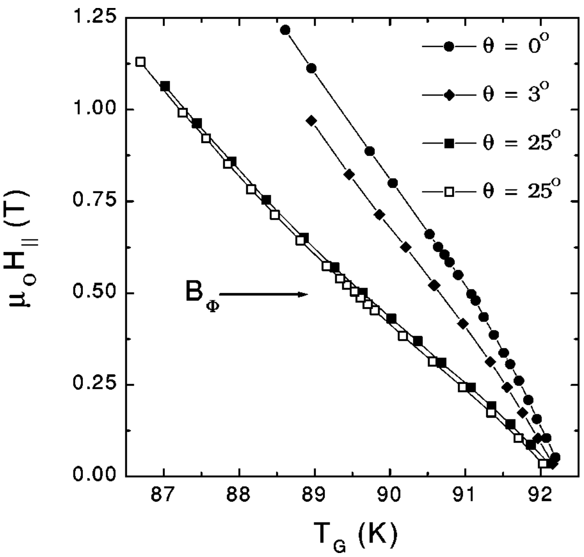

FIG. 3. T_g plotted against $\mu_0 H_\parallel$ measured with H parallel to the c axis and at angles of 3° and 25° relative to the c axis. The two curves at 25° were measured at $h_{ac} \simeq 0.6$ G (closed squares) and $h_{ac} \simeq 6$ G (open squares). As the field is tilted the columnar defects pin less effectively and the break in slope at B_Φ disappears.

present when $B > \mu_0 H_{c_1}$. We speculate that the sharp drop in slope and the associated inflection points near B_Φ may be a residual effect of this gap that survives to high temperatures.

Finally, we look at the case where the field is tilted away from the columnar defects. We reiterate that field components perpendicular to the defect axis as small as 0.1% of the parallel field lead to detectable deviations in the low-drive melting line shown in Fig. 1. As the field is tilted away from the defect axis, the columns should become less effective as pinning sites.[2] We show in Fig. 3 T_g vs $\mu_0 H_\parallel$ for several tilt angles $\theta = 0°$, 3°, and 25°. As expected, the knee at B_Φ disappears when the field is tilted.[15] Even at an angle of only 3° the knee is less prominent and has shifted to lower magnetic fields. The field-tilted data are reminiscent of those taken at zero tilt and high drive shown in Fig. 1; there is a slight downward curvature for $B < B_\Phi$ followed by an upward curvature for $B > B_\Phi$. However, in this case the two curved segments meet at a single inflection point so that there is no sharp jump in $dT_g/dH_\parallel$. Furthermore, the transition temperature is no longer sensitive to moderate increases in the driving field. At the largest tilt angle ($\theta = 25°$), the Bose-glass theory need not describe the system. In fact, T_g is well below the crystal melting line reported for unirradiated crystals,[16] where both vortex-vortex interactions and point disorder likely compete with the now less effective columnar defects.

In summary, we have observed a significant change of the Bose-glass melting line at $B = B_\Phi$, which serves to separate two linear segments of the phase boundary of dissimilar slope. The sharpness of the knee at the matching field and the reduction in slope as B exceeds B_Φ indicate that interstitial vortices are constrained (''caged'') by pinned vortices much less strongly than originally thought.[2] As expected, the effect disappears when the field is tilted away from the columnar defects. While Ref. 2 considered the case of low magnetic fields and temperatures, our measurements were taken near the transition into the normal state and at $B \gg \mu_0 H_{c1}$. These constraints, which are a reality for the experimentalist, also present a considerable challenge for the theorist. When the magnetic penetration depth is large compared to the vortex spacing (i.e., $B \gg \mu_0 H_{c1}$), long-range interactions become important.[17] Moreover, thermal fluctuations modify the predicted temperature dependence of the phase boundary as $T \to T_c$. We hope the experimental observation that $T_g(H_\parallel)$ simply depends linearly on magnetic field in both the regime below and the regime above the matching field helps guide the theoretical exposition.

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