PHYSICAL REVIEW B VOLUME 58, NUMBER 14 1 OCTOBER 1998-II

Vortex dynamics of heavy-ion-irradiated $YBa_2Cu_3O_{7-\delta}$: Experimental evidence for a reduced vortex mobility at the matching field

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(Received 17 April 1998)

Electrical transport measurements in heavy-ion-irradiated $YBa_2Cu_3O_{7-\delta}$ thick films reveal a clear maximum of the critical current when the applied magnetic field is approximately equal to the magnetic field at which all columnar defects are occupied. This result directly indicates that vortex mobility is greatly reduced when no vacant columns are available. We suggest that this result is a vestige of the Mott insulator phase predicted for the vortex system at zero temperatures. [S0163-1829(98)50238-X]

The realization[1] that irradiation-induced columnar defects are capable of a substantial increase of the critical currents of high-temperature superconductors sparked a considerable interest in the study of the physics of vortex dynamics in the presence of that type of disorder. This problem was theoretically addressed by Nelson and Vinokur,[2] who predicted a vortex solid phase, the Bose glass, where vortices are localized at the columnar defects. At high temperatures, this phase melts into an entangled vortex liquid. In the solid phase, vortex motion proceeds[2] as hopping of vortices between columnar defects. Within the vortex solid, a ''Mott insulator'' phase with reduced vortex mobility is predicted[2] when the density of vortices exactly matches the density of columns. In this context, a given density of columnar defects can be characterized by a magnetic field value, the ''matching field'' B_ϕ at which the density of vortices (B_ϕ/Φ_o) matches the density of defects. Thus, the Mott insulator phase is expected to occupy a horizontal line in the H-T magnetic phase diagram, defined by $H=B_\phi$.

To date, the experimental evidence for the Mott-insulator phase is restricted to low temperatures: for $T<4$ K magnetic relaxation experiments found[3] a reduction of the flux creep rate when $H\approx B_\phi$. It is not obvious that these effects would remain at higher temperatures, where thermally induced wandering of the vortices leads to a regime in which different segments of a vortex are pinned by different columnar defects. Indeed, the strong single-vortex pinning regime in which one vortex occupies one columnar defect is found[4] to extend only up to $\approx 0.5\times T_c$. Thus, it is not experimentally established how the Mott insulator phase will affect the physical properties of the vortex matter at higher temperatures, such as the critical current in the vortex solid phase near the glass transition to the vortex liquid state.

In this work we present electrical transport measurements of the vortex dynamics in heavy-ion-irradiated $YBa_2Cu_3O_{7-\delta}$ (YBCO) thick films. Our results show how the motion of vortices is modified as more columns are occupied: at intermediate temperatures we find that the magnetic field dependence of the critical current has a clear maximum when the applied field nears the B_ϕ. This demonstrates that vortex mobility is reduced close to the optimal occupancy of the columnar defects. At higher temperatures, as vortices are delocalized from the columns, the maximum in the critical current is replaced by a smooth shoulder that extends up to $H=B_\phi$. Ultimately, when the transition to a vortex liquid is reached, we find a clear kink in the vortex solid to liquid phase line at approximately B_ϕ.

The samples investigated in this work were high-quality YBCO thick films produced by pulsed laser deposition[5] on single-crystalline yttria-stabilized zirconia substrates. The samples studied had thickness ranging from 1 to 1.2 μm, and a zero field transition temperature in the range of 89 to 90 K (before irradiation). The films were patterned in a bridge geometry (5 mm$\times$200 μm) to improve the sensitivity of our transport measurements. Irradiations were performed using 1 GeV U atoms at the Atlas facility in the Argonne National Laboratory. The dose received by the samples was estimated from the beam's average ion density. Due to the narrow bridges utilized, small (10%) discrepancies between the real and estimated dose values are possible. We observed a reduction of the zero field transition temperature of approximately 0.7 K per Tesla of dose. Critical current measurements were performed by measuring the nonlinear current-voltage curves in the vortex solid state while holding temperature and magnetic field constant. From the I-V curves, the critical current is defined using the standard 1 μV/cm criterion.

Shown in Fig. 1 is the magnetic field dependence of the critical current I_c at various temperatures. A clear local maximum is seen around the matching field B_ϕ. The maximum disappears at higher temperatures, where just a plateau is seen, as shown in the inset to Fig. 1. The maximum in the critical current and its disappearance at higher temperatures were observed in all of the irradiated samples investigated, always approximately coinciding with the matching field. On the other hand, virgin samples show a monotonously decreasing field dependence at all temperatures.[6]

A very direct evidence that the maximum in I_c is a consequence of the dynamics of lines localized in the columnar defects comes from the angular dependence of the critical

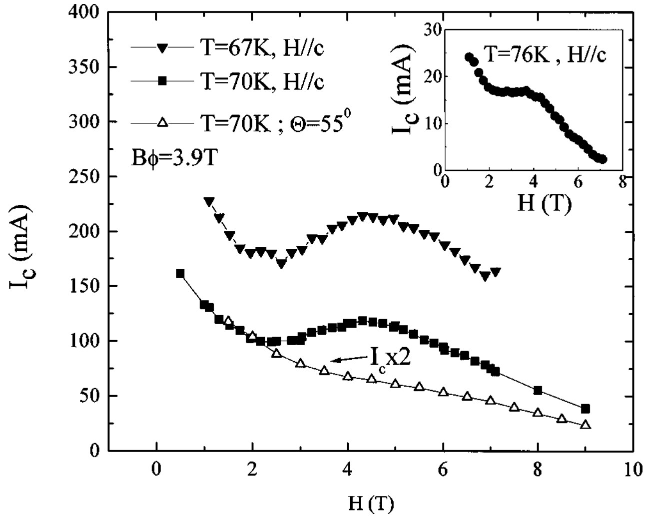

FIG. 1. Full symbols: magnetic field dependence of the critical current of a $B_\phi = 3.9$ T irradiated sample at $T = 67$ and 70 K and $H \| \mathbf{c}$ axis. Open triangles: $2 \times I_c$ vs H for the same sample and $T = 70$ K, with the magnetic field applied 55° off the c axis. Inset: I_c vs H at 76 K and $H \| c$ axis.

current. When the magnetic field is applied off the c axis (and vortices are no longer aligned with the columns) I_c shows a smooth (open triangles in Fig. 1), monotonic dependence. Due to the anisotropic nature of the critical current[6] the I_c values when $\Theta = 55°$ are substantially smaller than the I_c values for $\Theta = 0°$ ($H \| \mathbf{c}$ axis). To facilitate a direct comparison, we multiplied the $\Theta = 55°$ data by a factor of 2.

In a simple, single particle scenario, one would expect the critical current to be determined by the pinning force provided by a columnar defect. Thus, for magnetic fields $H < B_\phi$ the critical current should remain field independent, assuming that all columnar defects provide identical pinning forces. However, for interacting vortex lines in the presence of columnar defects a collective pinning model predicts[2,7] a monotonously decreasing $1/H$ dependence for the critical current. None of these models can account for the maximum seen near B_ϕ.

The above-mentioned models calculate the critical current starting from the depinning of the vortex lines from the columnar defects. While this is certainly a very important ingredient, our results suggest that the occupancy of columnar defects plays an equally significant role. Theoretically, vortex motion is modeled following a hopping mechanism: a vortex line jumps between columnar defects by creating, for example, double-kink excitations.[2,7] Implicit in this description is the need for empty columns available to receive the moving vortex. Within this vortex-hopping scenario, we propose that the observed peak in the critical current is a consequence of the vortex mobility being reduced near the perfect occupancy of the columnar defects, as predicted for the Mott insulator phase.[2]

The Mott insulator phase is expected to occupy a thin region of the phase space at exactly $H = B_\phi$. Instead, our experiment shows a broad feature. Similarly, broad features around B_ϕ are seen in low-temperature flux-creep measurements.[3] We tentatively attribute this broadening to screening effects: for the column densities studied in our work, the intercolumn distance d is about seven times smaller than the penetration length λ. Due to this, the repulsive interaction between vortices produces the screening[8,9] of the pinning potential of the columnar defects. We expect that vortex repulsion can play two distinct roles in our experiment. First, it can affect the dynamics of vortex hopping, since even for fields below B_ϕ, a vortex trying to move into an unoccupied column will be repelled by vortices pinned in the nearby columns. This effect is relevant to our experiment: our data show that the increase in I_c starts at about $B_\phi/2$, where on average every other columnar defect is occupied. A second consequence of vortex-vortex interactions is of static nature. It may not be energetically favorable for a vortex line to occupy a columnar defect that is located near an occupied column, due to the c_{11} compression elastic constant of the vortex lattice.[4] Recent simulations[9] find that for ratios λ/d of the order relevant to our experiment, 10% of the vortices are not pinned by columnar defects even when the applied field is only $B_\phi/2$. Ultimately, the nonperfect occupancy of columns will lead to a broadening and smoothing of the features of the Mott-insulator phase, or as recently proposed, its destabilization.[9] Thus, our observation may not correspond to the pristine Mott-insulator phase, rather to its vestiges in the limit of strongly interacting vortex lines.

We now concentrate on how this crossover in the vortex dynamics in the solid regime affects the glass to liquid transition. To determine the glass transition temperature T_g, we first perform measurements of the Ohmic (linear I-V) resistance in the vortex liquid state. The Ohmic resistance, finite in the liquid phase and zero in the vortex solid, is expected[2] to go to zero at T_g following a power law of the form $R \propto (T - T_g)^{\nu(z-2)}$ where ν and z are the static and dynamic critical exponents, respectively. Shown in the upper panel of Fig. 2 is the plot of the magnitude $(d \ln R/dT)^{-1}$, as calculated directly from the experimental data, versus temperature. In the critical region, where R follows the above power law, this plot of the data will give a straight line, with T_g as an intercept of the horizontal axis and $\nu(z-2)$ as the slope. A linear relationship is observed in a ~ 2 K interval above T_g. More importantly, the combination of critical exponents $\nu(z-2)$ is field independent, while only T_g is a function of the magnetic field. In the inset to that panel it is shown that the exponents are not only field, but also dose independent. These experiments measure the combination of the critical exponents $\nu(z-2) = 6.4 \pm 0.5$. From the scaling of nonlinear I-V curves we can obtain an *independent* measurement of the exponents ν and z and the glass transition temperature T_g. The result is shown in the lower panel of Fig. 2. A very good collapse of the nonlinear I-V curves is obtained with the values $T_g = 78.2 \pm 0.2$ K, $\nu = 1.2 \pm 0.1$, and $z = 7.2 \pm 0.3$ in excellent agreement with the independent Ohmic resistance measurements. Furthermore, the values of the critical exponents are remarkably similar to those measured for the Bose glass in the same samples before irradiation, in this later case due to naturally occurring $\mathbf{c}$ axis correlated pinning (e.g., twin boundaries, edge dislocations, etc).[10]

Shown in Fig. 3 is the magnetic field dependence of the glass lines for samples irradiated with various doses B_ϕ. For each sample and magnetic field, the Bose glass phase transition temperature was obtained from the scaling analysis presented in the previous paragraph. As the dose is increased we see a systematic shift of the glass line to higher temperatures.

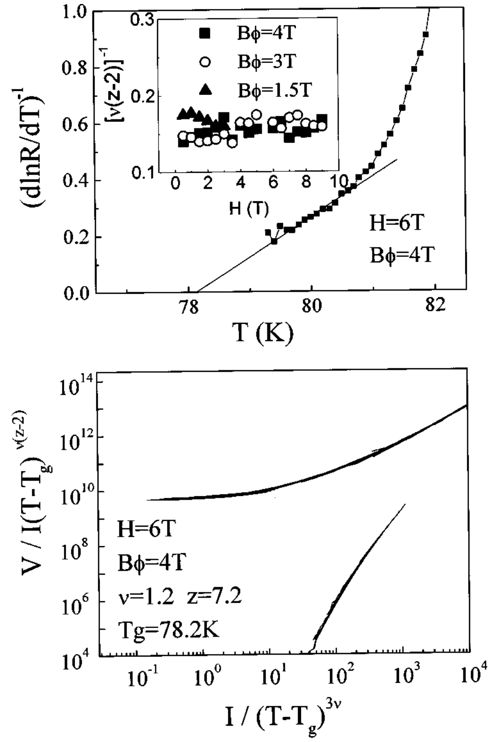

FIG. 2. Top panel: Inverse of the logarithmic derivative of $R(T)$. The slope of the linear fit (shown in full line) gives a combination of the critical exponents $\nu(z-2)$, while the intersection to zero gives the glass transition temperature T_g. Inset: Field dependence of $\nu(z-2)$ for three samples, irradiated with different doses, as indicated. Lower panel: scaling of the nonlinear current-voltage characteristics according to the Bose-glass model (see text).

A remarkable feature is the presence of a clear kink in the Bose glass lines (also seen previously in single crystals[11]), that occurs at fields slightly below the matching field for all doses investigated. Remarkably, while there is a change in the shape of the Bose-glass line the critical exponents remain constant, as shown in the inset to Fig. 2.

From our experiments we obtain a composite phase diagram that clearly shows the importance of column occupancy in the dynamics of the vortex system. Shown in Fig. 4 is the plot of the Bose glass line for a sample irradiated with a 3.9 T dose. In full circles we show the location of the maximum in the field dependence of the critical current. The open circles represent the plateau in I_c seen at higher temperatures. The error bars indicate the half-width of the peak and plateau. Thus, these features in the critical current define a practically horizontal region (shaded in the figure) in the H-T plane that divide the phase space occupied by the vortex solid. We propose that the shaded region is a vestige of the Mott-insulator phase. For fields below that region vortex motion occurs through vortex hopping between columnar defects, a process that ultimately gives rise to the maximum in I_c. At higher fields, it is likely that interstitial vortices, i.e., vortices not pinned by columnar defects, will dominate the dynamics, producing the shift of the glass line of irradiated samples towards the line of the virgin materials.[12]

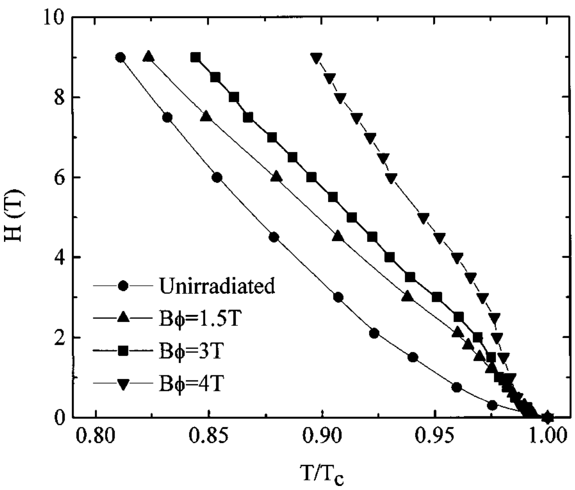

FIG. 3. Bose-glass lines for unirradiated and irradiated samples of different doses, as indicated.

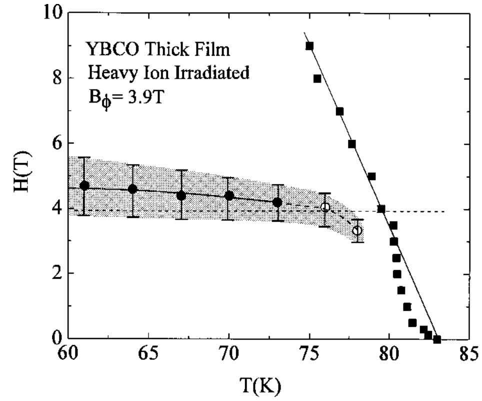

FIG. 4. Composite phase diagram of a sample with a $B_\phi=3.9$ T dose. Full circles: location of the maximum of I_c vs H. Open circles: plateau in I_c vs H seen at higher temperatures. The half-width of these features in I_c is given by the vertical bars around each point. The shaded region indicates the vestige of the Mott-insulator phase; see text. Full squares: Bose-glass line for the same sample. The solid line indicates the behavior of the Bose-glass line at fields higher than B_ϕ. The horizontal broken line indicates $H=B_\phi$.

It is interesting to discuss the possibility of whether the vestiges of the Mott-insulator line that we observe in the solid phase could persist into the vortex liquid state. Clearly, as seen in our data, it affects the shape of the Bose-glass line. Recent measurements of the reversible magnetization (i.e., above the Bose-glass line)[13] of irradiated samples of the highly anisotropic $Bi_2Sr_2CaCu_2O_{8-\delta}$ have found that the equilibrium magnetization is reduced when compared to that of unirradiated samples. These results are consistent with a model[14] of a liquid of pancake (two-dimensional) vortices that can occupy a discrete set of sites. Notably, this model predicts that at $H=B_\phi/2$ vortices in this extreme two-dimensional (2D) system will show a more coupled, linelike behavior. Indeed, this behavior is seen in c-axis transport[15] measurements. While in this paper we deal with a more 3D system, it is tantalizing to project that the Mott-insulator line that we see in the solid phase for $H\approx B_\phi$ could translate into the above-mentioned features in the vortex liquid state.

In conclusion, we have found a clear maximum in the magnetic field dependence of the critical current in heavy-ion-irradiated YBCO thick films. At low temperatures, the position of this maximum is nearly temperature independent and located at $H \approx B_\phi$. We explain this maximum in the critical current I_c as due to a reduced vortex mobility when all columns are occupied. This behavior is a vestige of the Mott-insulator phase predicted for the vortex system at low temperatures. As the vortex-solid to liquid transition is approached, the maximum in the critical current disappears, and a distinct kink is seen in the Bose-glass line slightly below the matching field. This kink in the Bose-glass line is interpreted as a consequence of the changing behavior of the vortex dynamics for $H \approx B_\phi$ seen at lower temperatures. In spite of this feature, the critical exponents are field and dose independent, reflecting the collective nature of the glass transition.

It is a pleasure to acknowledge useful discussions with Lia Krusin-Elbaum, Wai Kwok, and Franco Nori, and we gratefully thank Ken Gray, Wai Kwok, Bob Olsson, and David Steel for performing the heavy-ion irradiations. This work was supported by a NSF Grant No. DMR-9702535 (UIC) and by the U.S. Department of Energy (LANL and UIC).

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