Disordered Vortex Phases in Yba$_2$Cu$_3$O$_x$

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Abstract

The disordered vortex phases induced by line and point pinning in YBa$_2$Cu$_3$O$_x$ are explored. At high defect densities there is a single disordered solid separated from the liquid phase by a melting line. At low defect densities the topology of the phase diagram changes dramatically, with a vortex lattice phase adjoining disordered phases at high or low field. Critical points at the termination of first order melting separate the lattice and disordered phases. The line defect disordered phases follow the expected Bose glass behavior, while the point defect disordered phases do not exhibit the expected vortex glass behavior.

Introduction

The vortex state of type II superconductors displays a rich variety of collective behavior arising from the competition among vortex interactions, disorder due to pinning, and thermal fluctuations. (For reviews, see [1-6]). The simplest of the collective states is the vortex lattice [7], where the hexagonal arrangement minimizes the vortex interaction energy. This regular lattice can be destroyed by thermal disorder, producing a vortex liquid with local temporal fluctuations, and by quenched disorder due to pinning, producing solid vortex phases with strong static spatial fluctuations in the vortex positions. The disordered solid phases are especially interesting, because of the subtlety and diversity of the novel vortex behavior they display. This behavior can be continuously tuned, by introducing specific types and densities of pinning defects into the superconductor, and by adjusting the experimental magnetic field to control the vortex density and the temperature to control the thermal fluctuations.
The disordered vortex solids have been widely discussed in terms of two conceptual models: the vortex glass induced by point disorder [8-11], the Bose glass induced by extended line or planar disorder [12-14]. A third possibility is the polymer glass where liquid-like disorder freezes in continuously as the dynamics slow down with decreasing temperature [15]. The vortex glass and Bose glass represent well-defined thermodynamic phases that melt to a liquid by continuous phase transitions, while the polymer glass is a highly viscous “frozen liquid” that is thermodynamically indistinguishable from the liquid and does not undergo a melting transition. Experimentally, the characteristic feature of the vortex and Bose glasses is their distinctive melting behavior, displaying a critical region with non-linear I-V curves that collapse onto universal scaling functions. In contrast, the polymer glass has no melting phase transition or scaling behavior, though it may show strong temperature dependences of its properties near the irreversibility line. Unlike these strongly disordered solids, the vortex lattice and the weakly disordered Bragg glass [16] melt in a first order transition with thermodynamic discontinuities in the entropy and vortex density [17].

At high defect density, the phase diagram of YBa$_2$Cu$_3$O$_x$ (YBCO) shows two prominent phases, the disordered solid and the vortex liquid. Here the melting transition of the disordered solid can be studied in detail as a function of temperature and field. At dilute defect densities, however, the phase diagram becomes much more complex, with multiple solid phases below the melting line. These vortex phases are intimately related, allowing two or even three solid phases to coexist along with the liquid phase in a single phase diagram. This provides experimental access not only to the varieties of solid-liquid melting behavior, but also to the unusual phase boundaries between the lattice and disordered solid phases. The changes at these order-disorder phase boundaries are subtle: while even a small amount of disorder destroys the symmetry and long range order of the lattice [18], the weakly disordered state continues to melt via a first order transition [19] until a threshold of pinning disorder is reached. There a critical point appears, beyond which the disordered phase melts via a second order transition as expected for a glass. One such critical point in the vortex phase diagram has been widely discussed (see [5] for an overview). In many nominally clean crystals of YBCO, first order melting terminates at a sample dependent upper critical point above which a disordered solid phase appears. The pinning disorder in these crystals is uncharacterized and the nature of the high field disordered phase is not yet clearly understood. Very recently, a second lower critical point has been identified at low fields in crystals of YBCO with dilute line defects [20] and with point defects induced by proton irradiation [21]. The low field line disordered phases have been identified as Bose glass states, and there is a natural physical picture for the evolution from disordered glass to ordered lattice as the vortex density increases with field. In contrast, the low field point disordered phases do not follow the expected vortex glass scaling behavior, and their relationship to the ordered lattice presents a challenge to our current understanding.

In this paper we focus on the disordered states induced by controlled introduction of point and line defects into the superconductor YBCO. The vortex states disordered with line defects display non-linear I-V curves near the melting transition and follow the scaling
form expected for a Bose glass transition. (For the applied field tilted off the line defect direction, however, there are significant deviations from predicted Bose glass behavior [22,23].) In contrast, point disordered solid vortex states do not show non-linear I-V curves near their irreversibility lines, and do not conform to the predictions of vortex glass models. At much higher point defect densities, we find one component of vortex glass scaling, not in the I-V curves but in the linear resistivity with temperature [24]. This suggests that a threshold of pinning disorder may be required to produce the vortex glass state.

Experiment

Our experiments were carried out on untwinned single crystals grown at Argonne National Laboratory that showed sharp first order melting transitions before the introduction of point or line defects. This ensured that the disordered vortex states we observed were induced by the pinning defects we introduced and not by residual defects of unknown origin in the as grown crystals. Line defects were introduced by heavy ion irradiation at Argonne’s Tandem Linear Accelerator (ATLAS), using 1.4 GeV $^{208}$Pb $^{56+}$ ions directed along the c-axis of the crystal. Two large crystals were selected from the same growth batch and each was cut into four smaller crystals that were then irradiated to different doses. The line defect densities, specified by the matching field $B_0$ where the vortex density equals the line defect density, were 50 G, 100 G, and 500 G in the first set of four crystals, and 100 G, 1000 G and 1 T in the second set. The fourth crystal from each set was kept unirradiated for reference [20].

Point defects were introduced at Western Michigan University’s tandem accelerator by irradiation with 9 MeV protons directed along the c-axis of a selected crystal. Successive irradiation doses were applied, from $0.25 \times 10^{15}$ p/cm$^2$ to $2.0 \times 10^{15}$ p/cm$^2$ [21]. A separate crystal was irradiated to much higher dose, $3.0 \times 10^{16}$ p/cm$^2$ [24].

Results

Figure 1 shows the dramatically different effect on the first order melting line of high-density line and point pinning disorder. The first order melting line in the pristine crystal is shown as triangles. It is flanked on the high side by the line disordered irreversibility line, and on the low side by the point disordered irreversibility line. Here the line and point defect densities are large enough to eliminate first order melting from the phase diagram. Line and point disorder drive the irreversibility line in opposite directions. Line disordered solids are more stable than the liquid, while point disordered solids are less stable than the liquid.

Line Disorder

The nature of the solid phases below the irreversibility lines like those in Figure 1 is most directly probed by their melting behavior. The unirradiated crystal displays first order melting with discontinuities in the entropy and vortex density, a sharp drop in the resistivity to zero on freezing, and a finite critical current in the solid. First order melting
indicates that the solid phase is an ordered lattice. In contrast, the first order character is absent in the melting lines for the disordered solid phases in the presence of line or point pinning sites. The nature of these subtle vortex transitions is revealed by their dynamic response in transport experiments near the melting line.

Figure 2 shows the I-V curves for a sequence of temperatures near the melting line of the line disordered crystal in Figure 1 at 0.5 T. These curves show the pattern of nonlinear behavior typical of a Bose glass. They are linear at high temperature in the liquid state and gradually become non-linear at low temperature as the glassy state develops. The non-linear behavior collapses onto two curves when scaled by powers of \((T - T_{BG})\), as expected for the critical region of a Bose glass melting transition. The scaling involves two critical exponents, one describing the correlation lengths \(l_\perp \sim 1/(T - T_{BG})^\nu\) and \(l_\parallel \sim 1/(T - T_{BG})^{2\nu}\) and one describing the correlation time \(\tau \sim \tau^\zeta\). The scaling fit gives \(\nu = 1.7\) and \(\zeta = 3.4\). The same critical exponents are found for other fields below and above the matching field \(B@ = 1 \text{ T} \) [25]. The critical exponents agree well with values derived on another crystal with the same matching field [22].

At dilute line defect density, the phase diagram undergoes a dramatic modification. Instead of the single melting line between the Bose glass and the liquid found at high defect density, a lower critical point appears, separating a region of first order melting at high field from a region of Bose glass melting at lower field. Figure 3 shows the phase diagram for a matching field \(B@ = 500 \text{ G}\). At low fields, the irreversibility line determined from the onset of nonlinear behavior is raised above the first order melting line of the pristine crystal, as might be expected qualitatively from Figure 1. However at higher field, the irreversibility line of the disordered crystal re-joins the first order melting line at the lower critical point. For fields above the lower critical point, the irradiated crystal melts in a first order transition, just like the unirradiated crystal. The lower critical point marks the transition from a low field disordered solid to a high field ordered lattice, allowing the lattice and the disordered solid to share adjoining regions of the same phase diagram. This new topology allows the evolution of the lattice from pinning disorder to be characterized experimentally, as discussed elsewhere [20]. Here we concentrate on the nature of the low field solid. The non-linear I-V curves measured near the irreversibility line below the lower critical point display the same pattern of linear to nonlinear behavior with decreasing temperature as seen in Figure 2. Under scaling they collapse onto two curves, producing critical exponents that do not vary with field in the range up to 20 times the matching field \(B@\). (At higher field, near the lower critical point, the scaling form and critical exponents are expected to change as the melting becomes first order.) The scaling fit in the low field Bose glass gives \(\nu = 1.2\) and \(\zeta = 4\). These critical exponents are consistent with Monte Carlo simulations of Bose glass behavior with screened vortex interactions [26], and are similar to values obtained for crystals with twin boundaries which act as planar correlated defects [27].

Point Disorder
The influence of point disorder on the vortex phase diagram is as dramatic as that of lines. At high point defect concentrations, the lattice phase is completely replaced by a disordered solid as indicated in Figure 1. At lower defect concentrations, the irreversibility line is split by two critical points, one at high field and one at low field. These two critical points define an intermediate field region of first order melting, implying a vortex lattice bordered by point disordered vortex states at low and high field. Figure 4 shows the phase diagram for proton induced point disorder at selected doses. The dotted line is the lower curve shown in Figure 1, where the lattice phase is completely eliminated.

The striking feature of this phase diagram is the existence of two disordered phases, one at low field and one at high field. These two phases reflect different kinds of point induced disorder, as revealed by their differing response to changes in the magnetic field. Increasing field destabilizes the lower phase, replacing it with a lattice, but stabilizes the upper phase with respect to the lattice. The two disordered phases differ in another important way. Point disorder created by electron irradiation produces the upper disordered phase, but not the lower one. This difference may be related to the difference in size and strength of the point pinning sites created by electron and proton irradiation. Strong pinning is required to overcome the vortex-vortex interactions near $T_c$, as we discuss in more detail elsewhere [21].

The point disordered phases are surprising in other ways as well. Their I-V curves show the effect of pinning, but not the scaling required for the vortex glass. Figure 5 shows the I-V curves for an unirradiated crystal melting in a first order transition (top panel), a crystal irradiated to $1.0 \times 10^{15}$ p/cm$^2$ melting in a first order transition above the lower critical point (middle panel), and the same irradiated crystal in the disordered phase below the lower critical point (lower panel). The I-V curves of the unirradiated crystal are typical of those for first order melting in nominally clean crystals. They are linear in the liquid state, with nonlinearity first appearing at the onset of the sharp drop to zero in the resistivity. The nonlinearity is concave downward in the log-log plot of Figure 5, as expected if the voltage goes to zero at a finite value of the critical current in the vortex lattice phase. In the disordered phase of the irradiated sample at 0.5 T, below the lower critical point of approximately 2 T, the I-V curves show nearly parallel lines in the log-log plot, indicating nearly linear behavior. At the lowest measurable temperatures, the slope of the log-log plots of the I-V curves increases slightly, indicating a deviation from linearity. However there is no downward curvature at low temperatures in the log-log plot, as is required if the I-V curves are to follow the vortex glass scaling form. While point disorder drives out first order melting in the region below the lower critical point, there is no evidence from the I-V curves that it creates a vortex glass state that melts to the liquid via the expected second order transition associated with a critical regime.

The nearly linear I-V curves at the irreversibility line of the disordered phase below the lower critical point would be consistent with the absence of a thermodynamic phase transition as postulated for the polymer glass with its long dynamic response time at low temperatures. Another alternative is a thermodynamic phase transition at lower temperature, below that where the resistivity falls to unmeasurably low values. In this
case transport experiments would not be capable of detecting the phase transition or its critical scaling regime. They could be investigated by thermodynamic heat capacity measurements, which might find a thermal feature even well below the irreversibility line if such a phase transition existed.

Point disorder has an influence on the first order melting behavior above the critical point as well as on the low field disordered phase. The strongest effect is on the melting temperature itself, which is systematically lowered with point defect density as indicated in Figure 4. There is a more subtle effect, however, in the I-V curves, shown in the middle panel of Figure 5 for 4 T, the same field as in the top panel for the unirradiated crystal. Nonlinearity sets in at a lower temperature than in the unirradiated crystal, consistent with the lowered melting point. The nonlinearity appears as a systematic increase in the slope of the I-V curves in the log-log plot with decreasing temperature, indicating that the depinning transition becomes sharper at lower temperatures. However the downward curvature associated with first order melting in the clean crystal does not occur in the presence of point disorder. This suggests that the critical current in the solid phase may not be as well defined in the irradiated crystal as in the clean crystal. A range of local depinning currents could arise in the crystal with point defects from variations in local defect density. This could produce a series of partial depinning transitions as a function of current and a smoother I-V curve compared to the unirradiated crystal where depinning is controlled by a few residual pinning sites.

The three panels of Figure 5 show progressively stronger effects of pinning on the I-V behavior at the solid-liquid transition line. The upper panel shows downward curvature when there are few pins and the behavior is dominated by the competition between vortex interaction and thermal fluctuations. In the middle panel pinning competes with vortex interaction and the downward curvature is lost, though there is still strong non-linear behavior at the first order melting transition. In the lower panel, point pinning dominates over vortex interaction and the I-V curves are nearly linear at the solid-liquid transition. The trend toward linear I-V curves with increasing dominance of point disorder is confirmed at much higher defect density, as we discuss in detail below.

At much higher doses of proton irradiation we find evidence supporting a vortex glass transition below the zero of resistivity. Figure 6 shows the resistivity for an unirradiated crystal which shows first order melting, and the same crystal after irradiation with 9 MeV protons to a dose of 3.0 x 10^{16} p/cm^2. This dose is much higher than has been used in earlier studies. After irradiation, the resistivity loses the sharp feature characteristic of first order melting of the lattice, as observed for the disordered phases at lower proton dose. Instead, the resistivity of the irradiated crystal goes smoothly to zero, crossing the unirradiated curve. The crossing implies that proton irradiation depresses the irreversibility line, consistent with Figure 1. As at lower proton doses, the I-V curves are linear after irradiation. This is shown in the upper left inset to Figure 6, where the irradiated and unirradiated I-V curves are compared at the temperatures indicated by open and closed squares on the resistivity curves. Before irradiation, clear non-linear behavior is observed below the melting point. After irradiation, nonlinear behavior is absent, even to temperatures well below the onset of nonlinear I-V curves in the unirradiated crystal.
Although there is no nonlinear behavior in the I-V curves, we do observe a form of scaling in the linear resistivity that is expected for the critical region of a vortex glass transition. When approached from above the linear resistivity close to the glass transition should scale as \( \rho \sim (T - T_G)^{s} \) where \( s = \nu(z - d + 2) \) and \( d \) is the dimensionality of the system. This simple scaling form occurs in the low current limit where the unknown scaling function itself approaches a constant [1,9]. The relationship between the linear and nonlinear scaling regimes is shown schematically in the lower right inset to Figure 6. In the low density disordered phases associated with the upper and lower critical points, this kind of scaling of the linear resistivity is not observed. However at the high dose of \( 3.0 \times 10^{16} \) p/cm\(^2\) we see this scaling clearly. The upper panel of Figure 7 shows the resistivity as a function of temperature near the glass transition and the fits to the scaling form. The lower panel shows the field dependence of the scaling exponent \( s \) for eight fields in the \( c \) direction and six in the \( ab \) plane. The values of \( s \) are independent of field, a key requirement for vortex glass scaling behavior. Theoretical work and numerical simulations based on 3D spin and gauge glasses yield \( \nu \sim 0.9 - 1.7 \) and \( z \sim 4 - 6 \) (for a review, see [1]). Thus \( s \) is expected to fall in the range \( s \sim 2.7 - 8.5 \), consistent with our measured values of \( 5.1 \pm 0.5 \) for \( H \parallel c \) and \( 5.4 \pm 0.9 \) for \( H \parallel ab \). The value of the vortex glass melting transition, \( T_G \), is indicated in Figure 6 and in the upper panel of Figure 7 with an arrow. As seen, it occurs 1-2 K below the sensitivity limit for measuring the resistivity.

**Discussion and Conclusions**

Our results reveal several interesting features of point and line induced disordered phases. The disordered state induced by line defects is well described by the Bose glass model. At high line defect densities the phase diagram consists of only two phases, the liquid and the disordered Bose glass solid. The melting behavior of the solid displays the hallmarks of the Bose glass transition, namely a critical region of non-linear I-V curves that collapse under scaling to two scaling functions and give critical exponents that are independent of field. Other expected features, such as a cusp in the angular dependence of the Bose glass transition temperature, are also observed [20]. At dilute line defect densities, the phase diagram is more complex, with a lower critical point separating a low field disordered state from a high field lattice state. (At higher field, a second disordered phase appears above an upper critical point. This disordered phase is not driven primarily by line defects, although line defects do affect the upper critical point. See [20] for details.) Like the high defect density Bose glass, the disordered state below the lower critical point melts with a critical region of nonlinear I-V curves that scale to give critical exponents consistent with a Bose glass. Thus the Bose glass predictions describe the observed features of the melting of the disordered solid phases induced by dilute and concentrated line defects.

Point disordered vortex phases present a different picture. At low defect densities there are two kinds of point disordered phases, one below the lower critical point and the other above the upper critical point. These two phases cannot represent the same kind of disordered state, because an increasing field stabilizes one phase but destabilizes the
other. Neither of these phases displays the hallmarks of vortex glass behavior, a critical region containing non-linear I-V curves that collapse onto two scaling functions and a low current linear resistivity scaling with \((T - T_G)S\). The absence of these features raises the question of what these phases are, and whether a variation of the traditional vortex glass model is required to make it consistent with the data [11]. At high proton dose, approximately 20 times that needed to eliminate first order melting from the phase diagram, scaling of the linear resistivity appears, but without the nonlinear I-V curves which are normally associated with the critical region. Fits to the scaling of the linear resistivity yield values of the exponent \(s\) that are field independent and consistent with vortex glass expectations. The values of the vortex glass transition temperature derived from the scaling fit are 1 – 2 K below the nominal zero of resistivity, the sensitivity limit of our experiment. This form of scaling appears only at high proton dose, suggesting that a threshold of pinning disorder may be required to create the vortex glass state.

For both line and point pinning, we have shown that the vortex phase diagram in the presence of disorder displays new levels of complexity. The simple melting line that separates a single disordered solid from the liquid at high defect density is divided into two or three lines separated by critical points at low defect density. Here the vortex lattice coexists with disordered phases in the same phase diagram. The new topology of the phase diagram, with adjacent ordered and disordered phases, makes it possible to follow the evolution of order from disorder as a function of temperature, field and defect density.

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References

7. A.A. Abrikosov, Zh Eksp Teor Fiz 32, 1442 (1957); Sov Phys JETP 5, 1174 (1957).
Figure Captions

Figure 1  Vortex phase diagram showing the effect of line disorder (squares) and point disorder (diamonds) on first order melting (triangles). Line disorder was created by heavy ion irradiation by 1.4 GeV $^{208}$Pb $^{56+}$ to a matching field $B_\phi = 1$ T. Point disorder was created by irradiation with 9 MeV protons to a dose of $2.0 \times 10^{15}$ p/cm$^2$. The irreversibility lines for the disordered crystals are defined by the resistivity criteria $\rho = 0.1 \mu \Omega$-cm for point pins and the onset of nonlinearity for line pins.

Figure 2  Upper panel: nonlinear I-V curves for a YBCO crystal irradiated to a matching field $B_\phi = 1$ T. The curves were taken at the temperatures shown in an applied field of 0.5 T. The bold dots are are the scaling fit at $T_{BG}$. Lower panel: the I-V curves in the upper panel collapse onto two curves as shown when scaled by powers of $(T - T_{BG})$. The Bose glass temperature and the critical exponents derived from the fit are indicated.

Figure 3  Phase diagram at low fields for a vortex lattice showing first order melting ($B_\phi = 0$) and for a line disordered vortex system with a matching field $B_\phi = 500$ G. The irreversibility line determined from the onset of non-Ohmic behavior is displaced up at low field, consistent with Figure 1, but re-joins the first order melting line at the lower critical point. The solid triangles indicate Bose glass melting, the open symbols first order melting.

Figure 4  Phase diagram for the vortex system with point disorder induced by proton irradiation at the doses shown. The lower critical point for $1.0 \times 10^{15}$ p/cm$^2$ can be seen as well as the lower and upper critical points for $1.5 \times 10^{15}$ p/cm$^2$. The upper critical point for $1.0 \times 10^{15}$ p/cm$^2$ is above the highest measuring field of 8 T.

Figure 5  I-V curves showing the effect of point disorder on the solid-liquid transition. Upper panel: I-V curves at the first order melting line of the unirradiated crystal, where point disorder is nominally absent. Middle panel: I-V curves in an irradiated crystal at 4 T in the first order melting region above the lower critical point. Lower panel: I-V curves in the irradiated crystal at 0.5 T in the disordered phase below the lower critical point. The lower critical point for the irradiated crystal is approximately 2 T.

Figure 6  The temperature dependent resistivity for the unirradiated crystal showing sharp first order melting, and for the crystal irradiated to a dose of $3.0 \times 10^{16}$ p/cm$^2$ showing a smooth decrease to zero. Temperatures are labeled in reduced units, $t = T/T_c$. The arrow labeled $t_g$ marks the vortex glass transition temperature derived from the fit. Upper left inset: I-V curves for the unirradiated crystal showing non-linear behavior associated with the critical current in the vortex lattice, and for the point disordered crystal showing linear behavior down to the lowest measurable temperature. Lower right inset: the expected linear and nonlinear behavior of the I-V curves in the critical regime. The linear behavior is a consequence of scaling in the low current limit.
Figure 7  Upper panel: resistivity of the crystal irradiated to $3.0 \times 10^{16}$ p/cm$^2$ (circles) and the fit to the scaling form $\rho \sim (T - T_G)^s$ (lines) for the applied field $H$ parallel to the $c$ direction. The values of the vortex glass transition temperature $T_G$ derived from the fit are indicated with arrows. Lower panel: the scaling exponent $s$ derived from the fit as a function of field strength for the field direction along $c$ axis and in the $ab$ plane.
Figure 1 Crabtree et al
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