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# A vortex solid-to-liquid transition with fully anisotropic scaling

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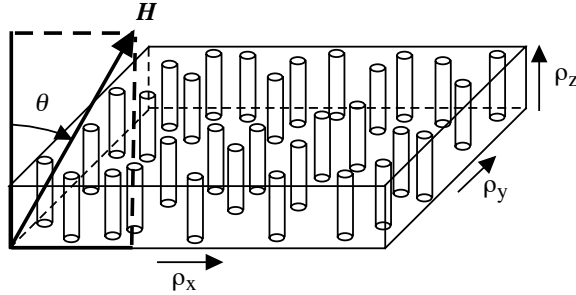
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**Abstract.** The vortex solid-to-liquid transition has been studied in heavy ion irradiated untwinned single crystals of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  with an inclined applied magnetic field. For magnetic fields tilted at angles about  $45^\circ$  away from the columnar defects, we find that the electric resistivity in the vortex liquid regime approaches zero with power laws in the reduced temperature  $T - T_c$  that have *different* exponents in all three spatial directions. Since the symmetry in the problem has been broken in two non-collinear directions by i) the direction of the columnar defects and ii) the direction of the applied magnetic field, our findings give evidence for a new type of critical behavior with fully anisotropic critical exponents. A possible view of the vortex topology for the transition is also suggested.

## 1. Introduction

The vortex solid-to-liquid transition separates a truly superconducting low temperature phase (vortex solid) from a dissipative high temperature phase (vortex liquid) in the  $H - T$  phase diagram of high temperature superconductors. In clean materials, the vortex solid-to-liquid transition is a first order melting transition, while it is believed to turn into a second order glass transition in the presence of strong static disorder. Different types of disorder give different glass behavior, e.g. in superconductors with columnar defects created by high energy ion irradiation, vortices are very effectively pinned when aligned along the columnar defects and less effectively pinned when aligned perpendicular to them, giving rise to a low temperature Bose glass phase [1]. Since the field and the columnar defects break the symmetry, the Bose glass transition is *anisotropic* with different critical exponents parallel and perpendicular to the columnar defects. This difference is also reflected in the topology of the vortex depinning of a Bose glass; a vortex pinned by a columnar defect is depinned by the creation of a half-loop while a vortex perpendicular to the columnar defect is depinned as it were from a point defect.

For a magnetic field tilted away from the columnar defects at a sufficiently small angle, the vortices will stay on the columns leading to a transverse Meissner effect. In this case, the transverse component of the magnetic field makes the three directions non-equivalent, which should give different critical exponents in all directions [2]. In a recent study on untwinned  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO) single crystals with columnar defects and an inclined magnetic field, we



**Figure 1.** The geometry of the experiment. The columnar defects are aligned along the  $z$  axis (crystallographic  $c$  axis) and the applied magnetic field is tilted with an angle  $\theta$  in the  $z - x$  plane. The resistivity is measured in all three spatial directions.

have found evidence for a regime where the resistivity disappears with power laws that have different exponents in all three spatial directions [3]. However, this occurs at high tilt angles and is not directly comparable to the theoretical results. In order to qualitatively understand the reason for the observed effect, we will discuss the topology of the vortex depinning in these experiments and argue that the depinning topology is likely to be different in all three directions.

## 2. Experimental results

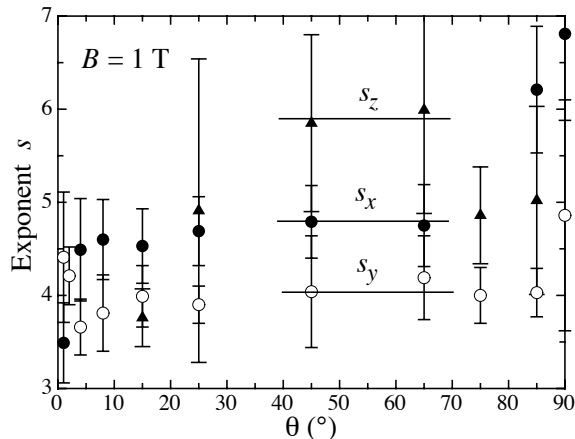
Untwinned as-grown YBCO single crystals were irradiated with 1 GeV  $\text{Pb}^{56+}$  ions at the Grand Accélérateur National d'Ion Lourds (GANIL), Caen, France. The fluence of  $n_d = 1 \times 10^{11}$  ions  $\text{cm}^{-2}$  created randomly distributed amorphous columnar defects, with a density corresponding to a matching field  $B_\Phi = \Phi_0/n_d = 2.0$  T (where  $\Phi_0$  is the flux quantum). The beam was incident along the crystallographic  $c$  axis (within experimental uncertainty) so that the ion tracks traverse the entire crystal thickness. The disappearance of the resistivity at the vortex solid-to-liquid transition was measured in all three spatial directions when a magnetic field  $H$  was tilted by an angle  $\theta$  as shown in Fig. 1. Using a picovoltmeter as pre-amplifier, a dc voltage resolution below 1 nV was obtained in the measurements. The measurement current (typically 100  $\mu\text{A}$ ) was sufficiently low to ensure an Ohmic behavior.  $\rho_x$  and  $\rho_y$  were measured on the same sample, while  $\rho_z$  was measured on a second sample as described in Ref. [3].

When the vortex liquid turns into a glassy vortex solid state below the vortex solid-to-liquid transition temperature  $T_c$ , the resistivity within the vortex liquid state drops to zero as a power law in  $|T/T_c - 1|$ , i.e.

$$\rho_i = \rho_0 |T/T_c - 1|^{s_i}, \quad i = x, y, z \quad (1)$$

where we have allowed for the possibility of having different exponents  $s_i$  in the three spatial directions of the sample. This relation gives a good description of the experimental data at resistivity levels less than 5 % of the normal state resistivity as viewed from the linearity obtained when plotting the inverse of the logarithmic derivative  $(\partial\rho/\partial t)^{-1} = (T - T_c)/s_i$  versus temperature.

The main result of our study is exemplified in Fig. 2, where the three different exponents are shown as a function of angle at an applied field  $\mu_0 H = 1.0$  T corresponding to half of the matching field  $B_\Phi = 2.0$  T. As seen, there exists a range of angles between  $45^\circ$  and  $65^\circ$ , where the exponents are almost constant and clearly different from each other. We obtain  $s_x = 4.8 \pm 0.4$ ,  $s_y = 4.1 \pm 0.4$  and  $s_z = 6.0 \pm 0.6$  in good agreement with the exponents obtained at an applied field of 2 T, where  $s_x = 4.7 \pm 0.2$ ,  $s_y = 3.8 \pm 0.2$  and  $s_z = 6.6 \pm 0.3$  were found [3]. In the latter case, the range where almost constant values of the exponents were found extended between  $25^\circ$  and  $65^\circ$ . This differences in angular ranges may possibly be related to the observation that



**Figure 2.** The angular dependence of the power law exponents obtained from fitting to Eq. 1 for an applied magnetic field  $\mu_0 H = 1.0$  T. Note that in the range  $45^\circ$  to  $65^\circ$ , the exponents are clearly different and almost constant, suggesting a critical behavior that is anisotropic in all three spatial directions.

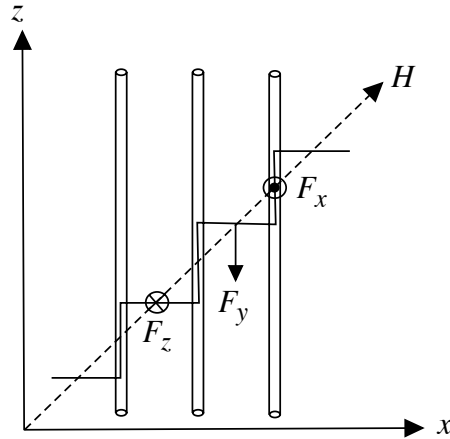
the accommodation angle  $\theta_a$  defined from the maximum in the resistivity versus angle curve is higher at lower applied fields [4], but this need further investigations.

Another observation from Fig. 2 is that the two exponents  $s_x$  and  $s_y$  are different and roughly constant over quite a large angular range (except for angles close to  $0^\circ$  and  $90^\circ$ ). The averaged effective Lorentz force on the vortices changes quite considerably in the  $x$  direction when tilting the field. Thus, an almost constant  $s_x$  implies that a model based on a Lorentz force acting on a straight vortex line must be rejected as the cause of our observations. On the other hand,  $s_z$  is changing considerably as a function of angle, starting from a low value at  $\theta \approx 0^\circ$ , increasing until it reaches a maximum in the regime discussed above, and finally decreasing again. The same trend is seen for a field of 2 T [3].

### 3. Discussion

From the results, we see that there is an angular regime where the exponents are constant and clearly different ( $45^\circ \leq \theta \leq 65^\circ$  in Fig. 2), i.e. in this regime fully anisotropic scaling is observed. This can be directly related to a general assumption based on different critical exponents for the glass correlation lengths associated with the three spatial directions. More specifically, assuming correlation lengths  $\xi_x = \xi^\chi$ ,  $\xi_y = \xi$  and  $\xi_z = \xi^\zeta$  where  $\xi \sim |T - T_c|^\nu$  and  $\nu$  is the static critical exponent and a correlation time for critical scaling down  $\tau \sim \xi^z$ , one obtains  $s_x = \nu(z - 1 + \chi - \zeta)$ ,  $s_y = \nu(z + 1 - \chi - \zeta)$  and  $s_z = \nu(z - 1 - \chi + \zeta)$  [2, 3]. Within this assumption, the only way to obtain three different values of  $s_i$  is to have different critical scaling exponents of the correlation lengths ( $1 \neq \chi \neq \zeta \neq 1$ ), i.e. the observed phase transition must be anisotropic in all three directions.

Let us now speculate about a possible way to visualize the topology of the vortex excitations responsible for the results in Fig. 2. First, it is important to notice that the glass temperature  $T_c$  in the regime where the exponents are different is, presumably, higher than the melting temperature  $T_m$  of a pure superconductor as indicated by experimental results [3]. This implies that the transition is controlled by thermal and pinning energies. Thus, elastic energies will be less important and  $T_c > T_m$  may also open up for plastic deformations of the vortex system. Therefore, it seems reasonable to assume that the vortex system can freeze into a staircase vortex structure at  $T_c$  also for angles  $\theta > \theta_a$ . In such a situation, vortex motion can be imagined



**Figure 3.** The various ways for vortex motion in a staircase vortex configuration with strong pinning along the columns. Lorentz forces when the current is applied along the  $x$ ,  $y$  and  $z$  directions are shown as  $F_x$ ,  $F_y$  and  $F_z$  respectively.

as shown in Fig. 3, where the direction of the Lorentz forces are shown when the measurement current density  $j$  is in the  $x$ ,  $y$  and  $z$  direction respectively. With  $j \parallel x$ , the Lorentz force probes thermal fluctuations out of individual pinning centers along the columns. With  $j \parallel y$ , the Lorentz force in principle probes thermal fluctuations on the vortex segments in between two columns and on the vortex segments along the columns. However, the first ones are expected to dominate the dynamics due to an easier mode of motion sliding along the columnar defects. Finally, with  $j \parallel z$ , the Lorentz force probes thermal fluctuations of the vortex segments in between the columns, but in this case vortex motion requires an additional thermal depinning from the columns. As seen, this results in three topologically different modes of vortex depinning, which presumably will have different dynamics leading to different exponents for the disappearance of the resistivity at  $T_c$ . From the three modes discussed, one would expect the vortex motion to successively become harder in the order  $y$ ,  $x$ ,  $z$ , which is also reflected by increasing values of the exponents in the same order.

Another view is to neglect the vortex segment in between the columns and only consider the depinning of vortex segments along the columns. On a short length scale, this is then identical to the situation of a transverse Meissner phase, which was studied theoretically in [2]. As indicated above, such an assumption leads to the same relative order between the exponents and can qualitatively explain our results.

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