ORDER-DISORDER COEXISTENCE AND LIMIT OF METASTABILITY IN VORTEX LATTICES

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1. INTRODUCTION

Magnetic vortices in pure type II superconductors at low temperatures are expected to form a broken-symmetry state with long range translational order *ie* a vortex crystal. As the temperature or field is increased the vortex crystal should melt into a vortex liquid [1-4]. But this simple phase diagram is significantly altered in real samples where material imperfections and the resulting random pinning potential destroy the long range order[5-7]. Thus in relatively clean systems the low temperature vortex lattice is replaced by a Bragg glass, where the lattice maintains its topological order but supports local elastic distortions to accommodate the random potential[8]. This state is expected to exhibit power law Bragg peaks in scattering experiments[9]. With increasing field, temperature or strength of random potential, the Bragg glass "melts" into a disordered state where Bragg peaks are no longer seen [10-14]. One of the first hints of this transition was seen about 40 years ago [15] in niobium in the form of the "peak effect", a sudden increase of the critical current just before it vanishes at the superconducting transition. As pointed out by Pippard [16], the increase in critical current is an indication of the better accommodation of vortices to the local pinning potential made possible by a loss of rigidity at melting. More recently it was found that the peak effect is a generic property of the vortex state in all weak pinning superconductors but its relation to the order-disorder transition is still controversial. Small Angle Neutron Scattering (SANS) experiments have shown that at low temperature an ordered state consistent with a Bragg glass [10-14] does indeed exist, but on the issue of melting and its relation to the peak effect the

SANS experiments are inconclusive and in some instances give contradictory results. Similarly with standard transport techniques it is also difficult to establish the link between these phenomena because during the measurements vortices have enough time to move and reorder in response to the driving current so that that the result does not necessarily reflect the initial state.

We have developed a transport technique that avoids current induced organization and gives access to the static vortex lattice. Our experiments show that the static vortex lattice does exhibit a peak effect and that it undergoes an order- disorder transition. We observe both supercooling and superheating of the vortex states when the temperature is varied through the transition. Contrary to recent SANS measurements on the vortex lattice in Pb [13,14] we find that the limit of superheating for the vortex lattice in $NbSe_2$ is below the superconducting transition indicating that there is a range of temperatures where the vortices can only form a disordered state.

2. EXPERIMENT

The experiments were carried out in the low temperature superconductor 2H-$NbSe_2$ on both undoped and Fe-doped single crystals. The Fe-doped sample (sample A) has zero field critical temperature and width of T_c=5.61mK and ΔT_c=62 mK , respectively while in the undoped sample (sample B) T_c=7.21 K and ΔT_c=92 mK. Our measurements employed a four probe technique with low resistance $Ag_{0.1}In_{0.9}$ solder contacts. The distance between the voltage contacts was 3 mm and 1.5 mm in samples A and B, respectively. The critical current, I_c, is defined as the current at which the voltage reaches 5 μV. The magnetic field was kept along the c axis of the sample and the current was applied in the a-b plane. The experiments monitor the current-voltage ($V - I$) curves at various current ramping rates as well as the temporal evolution of the voltage response to current steps. The current ramps with ramping rates higher than $10^3 A/s$ and the current steps were generated with waveform generators and the corresponding voltage response was amplified with a low noise fast amplifier (4nV/ $Hz^{1/2}$) and recorded with a 100MHz digital oscilloscope. In order to increase the signal to noise ratio the fast transport data were averaged over 10 runs (initiating the system with cooling cycle from above T_c for each run). For the slower current ramps we used a DAC board and/or a commercial current source (Keithley 2400) and the corresponding voltage response was read with a commercial nanovoltmeter (Keithley 181). The critical current, I_c, is defined as the current at which the voltage response reaches $5\mu V$.

Most transport measurements are carried out on vortex lattices that have undergone some type of current induced reorganization. For example, when the applied current is longitudinal, as is the case for rectangular electrode configurations, vortex motion entails crossing a surface barrier at the sample edge and gives rise to "edge contamination" - the formation of disordered phase at the entry edge [17,18]. Whenever edge contamination is absent, the onset of the peak effect is found to shift to a higher temperature. This is observed when edge contamination is preempted by carrying out fast measurements[19-21] or when it is avoided by using a Corbino lead geometry [18]. The speed of measurement determines the extent of vortex reorga-

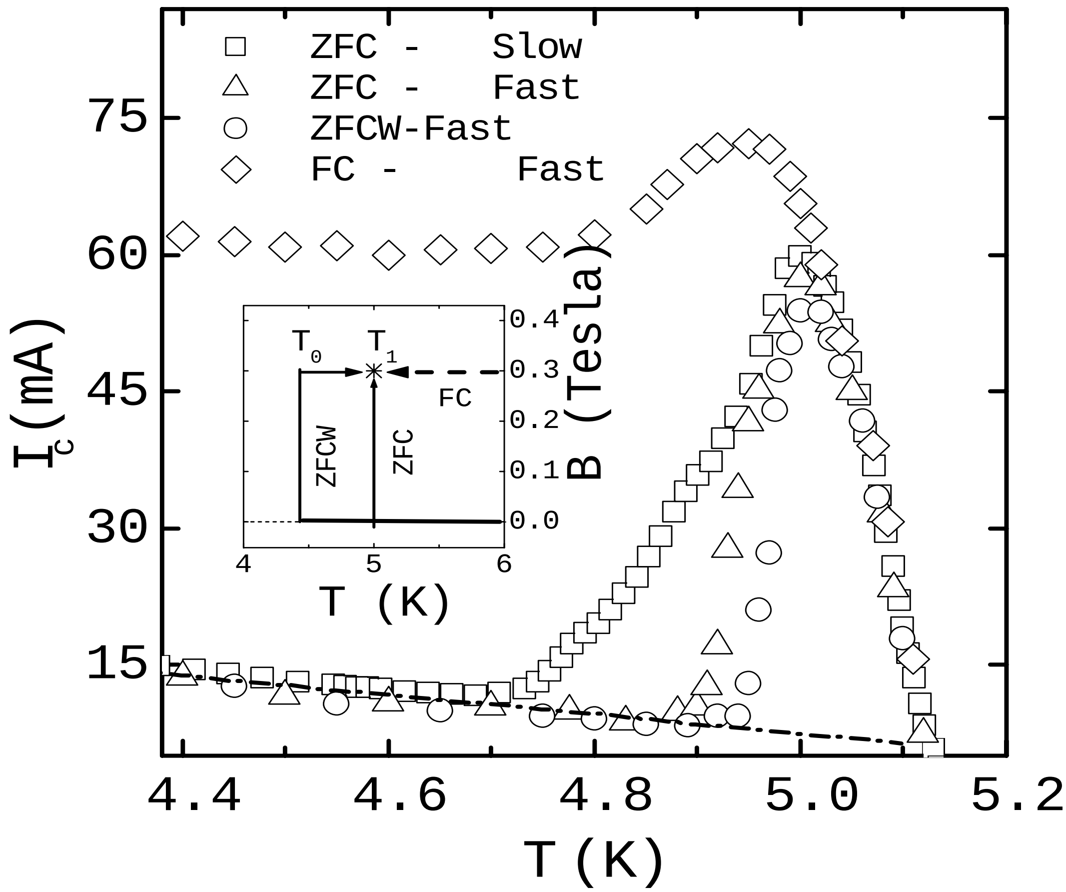

Figure 1. Temperature dependence of the critical currents: ZFC (slow)- data obtained with a slow current ramp (SCR, 10^{-4} A/s) for the zero- field cooled vortex lattice; ZFC (fast)- data obtained with fast current ramp (FCR, 200 A/s) for the ZFC vortex lattice; ZFCW - data obtained with a FCR for the zero-field cooled and warmed vortex lattice; FC (fast) - obtained with FCR for field cooled vortex lattice. Inset: illustration of the paths of ZFCW, ZFC and FC in the magnetic field versus temperature diagram.

nization. Typically if the distance traveled during the measurement time is much less than the vortex spacing reorganization effects are negligible and the V-I characteristics captures the initial vortex state much like a snapshot. In the Corbino geometry lead configuration the vortex motion is azymuthal so that edge crossing is not present. In the experiments discussed here we used a rectangular geometry and fast measurements. This avoids the large shear stress and breaking up of the vortex lattice that is inherent in the Corbino geometry [22]. The current ramps used in these experiments 200A/s were sufficiently fast for all measurements but those that were taken in the peak region.

3. RESULTS

The temperature dependence of the critical current measured at a field of 0.3T

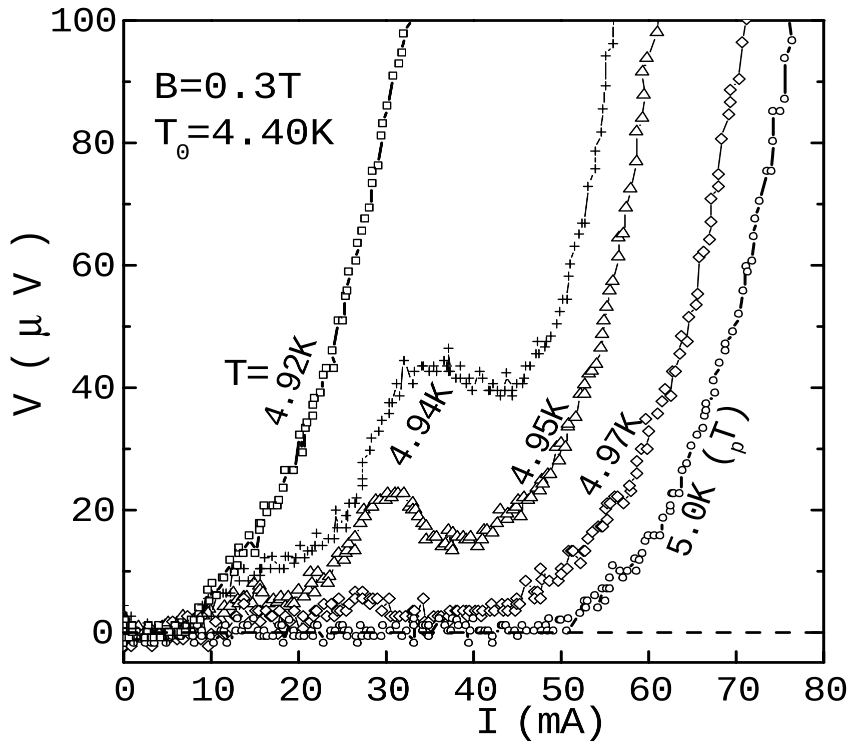

Figure 2. V-I characteristics at temperatures close to the peak temperature T_p obtained with the

in sample A (T_c =5.17 K at this field) is shown in Fig. 1 for vortex lattices prepared and measured by different procedures. Clearly the onset of the peak effect depends on the method of preparation: it is lowest for the zero field cooled (ZFC) state measured with a slow current ramp- open squares. The fast measured ZFC lattice open triangles- shows a peak whose onset is shifted to higher temperatures, confirming previous findings [19-21]. Higher still is the onset temperature of the peak for ZFCW (ZFC warm) lattice -open circles.

The ZFCW is a superheated state prepared at a low temperature T_0 =4.4K well below the peak effect, where edge contamination is known to be negligibly small and then heated to the target temperature T_1 where it is measured with a fast current ramp. The fact that the peak onset in the ZFCW data occurs at a higher temperature demonstrates that the temperature at which the lattice is prepared determines its state and that a more ordered ZFC state prepared at low temperatures can be superheated into the peak effect. As shown in Fig.2, some V-I curves obtained for the ZFCW state close to the peak are N-shaped, which is a signature of flow-induced organization [20]. This implies that close to the peak, the reorganization times are so short that the fast current ramp used in these experiments may still be too slow to capture the critical current of the static vortex lattice.

In order to avoid this measurement driven reorganization we followed a different procedure: the ZFCW lattice was not probed at T_1 but, after waiting at T_1 for a few minutes it is cooled back to T_0 where the V-I curves are measured with a fast current

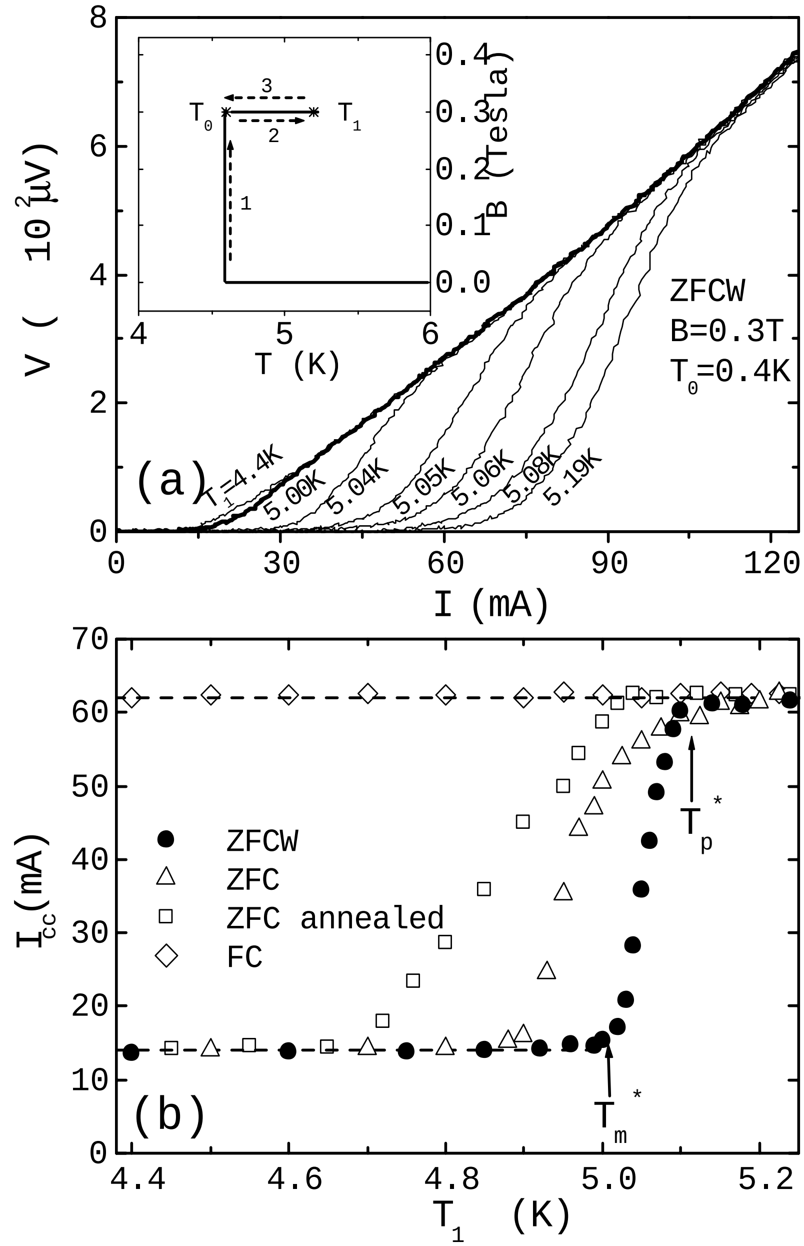

Figure 3. (a) Current-voltage curves obtained at T= 4.4 K with a fast currevt ramp for the ZFCW vortex lattice prepared a T_0=4.4 K and heated to various temperatures T_1. The thick curve B represents the data for $T_1 = T_m^*$. The inset illustrates the path in magnetic field versus temperature, i.e. the vortex lattice is prepared at T_0 followed by heating to T_1, finally the effects of these temperature excursions are compared by measuring the V-I curves at a fixed temperature T_0. (b) $I_c(T_1)$ for different methods of preparation as noted in the legend.

ramp. In Fig.3(a) we show the resulting V-I for several target temperatures. The critical currents measured by this procedure, henceforth referred to as "cold measured critical currents" and labeled $I_{cc}(T_1)$, are shown in Fig.3(b) by solid circles. We note that $I_{cc}(T_1)$ remains constant and equal to the critical current of the ordered state for temperatures T $\leq T_m^*$ ∼5K where it starts increasing and ultimately saturates at the value of the disordered state at T_p^* ∼5.3K. For comparison we also plot in the figure the $I_{cc}(T_1)$ values obtained with other procedures: open triangles- plain ZFC the state is prepared at T_1 but measured after cooling to T_0; open squares- annealed

ZFC- similar to plain ZFC but at T_1a slow current ramp is applied before cooling back down to T_0. The same qualitative behavior is seen in each case: an ordered state at low temperatures undergoes a transition to a disordered state at high temperatures. The onset and saturation temperatures in the superheated vortex lattice T_m^* and T_p^*, are the highest and cannot be exceeded. In the same figure we also show the data for the field cooled (FC) state (open diamonds) measured at T_1.

4. THE TWO STATE COEXISTENCE MODEL

In the Larkin-Ovchinnikov theory [23] the degree of order in the vortex lattice, as measured by the size of the Larkin domains, decreases with temperature. (The Larkin domain is the distance over which the mean square deviation of a vortex position from a lattice point is comparable to the coherence length.) Thus the FC vortex state (open diamonds in figure 2) is the most disordered.

The disordered state remains unchanged upon cooling unless disturbed by an applied current or changing field) indicating that it is a robust metastable state [24,25]. By contrast the ZFC state prepared at low temperatures is the most ordered. The constant values of $I_{cc}(T_1)$ obtained by superheating the ZFC lattice up to $T_1 < T_m^*$ and back to T_0 imply that the temperature driven lattice deformations taking place during these temperature excursions are reversible and elastic. At higher temperatures $T_1 > T_m^*$, the rapid increase in $I_{cc}(T_1)$ indicates an irreversible shrinkage of the average Larkin domain [23]. This result could either reflect a homogeneous loss of order or the formation of a mixed phase consisting of ordered domains embedded in a disordered state. The latter is consistent with recent Hall probe microscopy[26] and magneto-optics imaging experiments[27] that revealed a mixture of liquid and solid close to the melting transition. In view of these results we interpret the $I_{cc}(T_1)$ curves shown in Fig 3(b), in terms of a two phase coexistence model. The model follows directly from our data and can be summarized as follows:

a) When the vortex state is prepared by ZFC at a temperature T_0, well below the peak effect, it forms an ordered state.

b) The ordered state can be superheated up to T_m^* without introducing topological defects, so that temperature excursions to any temperature $T_1 \leq T_m^*$ and back to T_0 leave the system unchanged.

c) When the ordered vortex lattice is heated it develops disordered domains and forms a mixed state consisting of ordered and disordered domains. For temperatures $T_1 \geq T_m^*$ vortices no longer can find a path across the sample that does not contain some fraction of disordered phase leading to an increased critical current. The path across the sample containing the least amont of disordered phase is the first to allow vortex motion and thus determines the value of the critical current. We denote the fraction of disordered phase along this path by $\alpha(T_1)$.

d) The disordered domains remain frozen in place upon cooling back to T_0, so that the cooled state is a frozen version of the state at T_1.

Therefore the critical current measured at T_0 =4.4 K following a temperature excursion up to $T_1 \geq T_m^*$ is given by:

$$I_{cc}(T_1) = \alpha(T_1)I_{cd}(T_0) + (1 - \alpha(T_1))I_{co}(T_0)$$

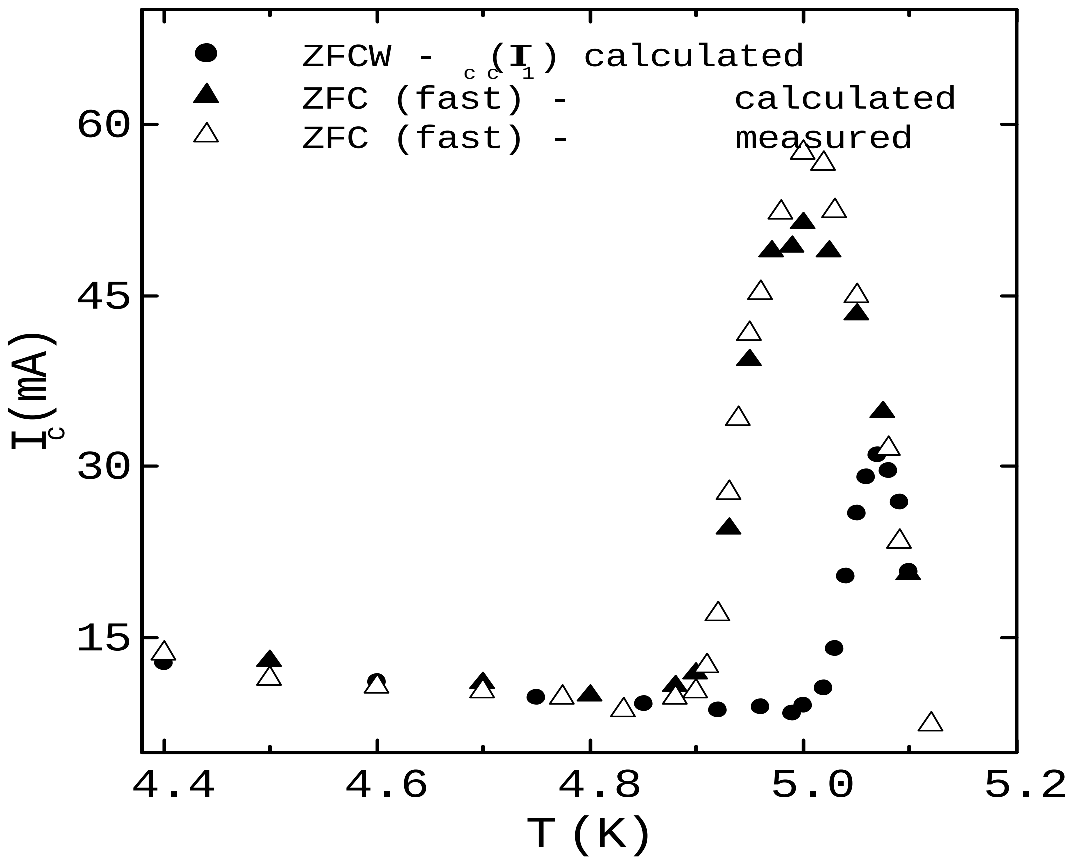

Figure 4. Calculated values of $I_c(T_1)$) for the superheated lattice in the absence of current induced reorganization. For comparison we also show the measured and calculated values of $I_c(T_1)$) for the ZFC lattice.

where $I_{cd}(T_0)$=62mA and $I_{co}(T_0)$= 14 mA are the critical currents of the disordered and ordered vortex lattice obtained from fast measurements of the FC and ZFC states respectively at T_0. We can now obtain $\alpha(T_1)$ from the measured values of $I_{cc}(T_1)$, $I_{cd}(T_0)$ and $I_{co}(T_0)$ and use it calculate the critical current of the superheated vortex lattice at T_1 in the absence of edge contamination:

$I_c(T_1) = \alpha(T_1)I_{cd}(T_1) + (1 - \alpha(T_1))I_{co}(T_1)$

Here $I_{cd}(T_1)$ and $I_{co}(T_1)$ are the critical currents obtained from fast measurements of the FC and ZFC states at T_1. At high temperatures where $I_{co}(T_1)$ is experimentally inaccessible we estimate its value by extrapolating the low temperature data (dashed line in Fig.1).

In Fig. 4 we show the results obtained by using this procedure for calculating $I_c(T_1)$. To check the method we applied it to the ZFC obtained with a fast current ramp where of $I_c(T_1)$ can also be measured directly. As seen in the figure it is clear that the measured values (open triangles) are in very good agreement with the calculated ones (solid triangles). The calculated data for the superheated lattice (solid circles) show a significant shift of the peak to higher temperatures. We conclude that the in the absence of measurement induced reorganization the peak effect in the superheated vortex lattice is shifted to a higher temperature and is much narrower than in the other vortex lattices.

The pure sample (sample B) exhibits a similar transition from an ordered state at low temperatures to a disordered state at high temperatures. As in the Fe-doped sample, the calculated $I_c(T_1)$ curve reveals that the peak effect in the static lattice is shifted to a higher temperature compared to that in the driven lattices.

Our data demonstrates that the onset of the peak coincides with the appearance of disordered domains. The disordered domains are nucleated at sample edges in the presence of driving currents, even when this is not thermodynamically favorable. The more efficient the nucleation mechanism the lower the peak temperature: it is lowest for the annealed ZFC lattice. Thus the onset of the peak cannot be attributed to a phase transition. As the temperature is increased the disordered domains continue to expand until, at the peak temperature the entire sample is disordered. In the superheated lattice measured by our technique edge nucleation of disordered phase is completely suppressed. The only way the superheated lattice can become disordered is through thermal fluctuations. It follows that the proliferetaion of disordered domains for $T \geq T_m^*$ coincides with the temperature where the disordered state is thermodynamically stable and accessible through thermal fluctuations. Thus T_p^*, the temperature above which an ordered state is never observed marks the limit of metastability.

5. CONCLUSIONS

By using a novel measurement technique the experiments described here probe the static vortex lattices in the absence of current driven organization. We find that a superheated ordered vortex lattice exhibits a peak effect and undergoes a sharp transition into a disordered state at a temperature that is significantly higher compared to that of the peak effect in standard transport measurements but still below the superconducting transition. These experiments demonstrate that a limit of metastability of ordered domains does exist in the vortex phase diagram.

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