ORDER-DISORDER TRANSITIONS IN A VORTEX LATTICE

E. Y. Andrei[1], *Z. L. Xiao*[1], *W. Henderson*[1,2], *Y. Paltiel*[3], *E. Zeldov*[3], *M. Higgins*[4], *S. Bhattacharya*[4], *P. Shuk*[5] *and M. Greenblatt*[5]

[1]Dept. of Physics and Astronomy, Rutgers University, Piscataway, NJ 08855
[2]Dept. of Physics, UCLA, 405 Hilgard ave. Los Angeles CA 90095
[3]Dept. of Condensed Matter Physics, Weizmann Institute, Rehovot, Israel
[4]NEC Research Institute, 4 Independence Way, Princeton NJ 08540
[5]Department of Chemistry, Rutgers University, Piscataway, NJ 08855

1. INTRODUCTION

A random potential or the presence of certain types of boundaries can alter the physical properties of interacting particles. The result is often metastability, glassy behavior and nonlinear dynamics which cannot be treated in the context of standard statistical mechanics or mean field approaches. Experimental studies in such systems are complicated by the appearance of diverging time scales and by the difficulty of accessing experimental "knobs" that can facilitate phase space exploration and lead to equilibration. The situation is simpler in the system of vortices in type II superconductors because the relative strength of the random potential can be controlled by changing the magnetic field or by applying a driving current. In the experiments described here we show that an applied current can release the vortex system out of a metatable state, enables phase space exploration and reduces the dynamic time scales. In addition we show how the presence of boundaries can profoundly affect the measurements of the phase diagram and the vortex dynamics.

Due to their mutual interactions vortices prefer to sit on the sites of a triangular lattice forming an Abrikosov solid. When the interactions are weak compared to thermal fluctuations the vortex solid melts forming a liquid phase. This leads to a phase diagram consisting of a vortex solid bounded by a vortex liquid which is expected to be stable just below the upper critical field line, $H_{c2}(T)$, and just above the lower critical field line $H_{c1}(T)$ [1]. This simple phase diagram becomes considerably more interesting in the presence of various types of disorder introduced by material imperfections. It is well known that even the smallest amount of material defects is sufficient to disrupt the delicate long range translational order of the vortex lattice [2]. This is expected to lead to the formation of disordered phases such as a vortex

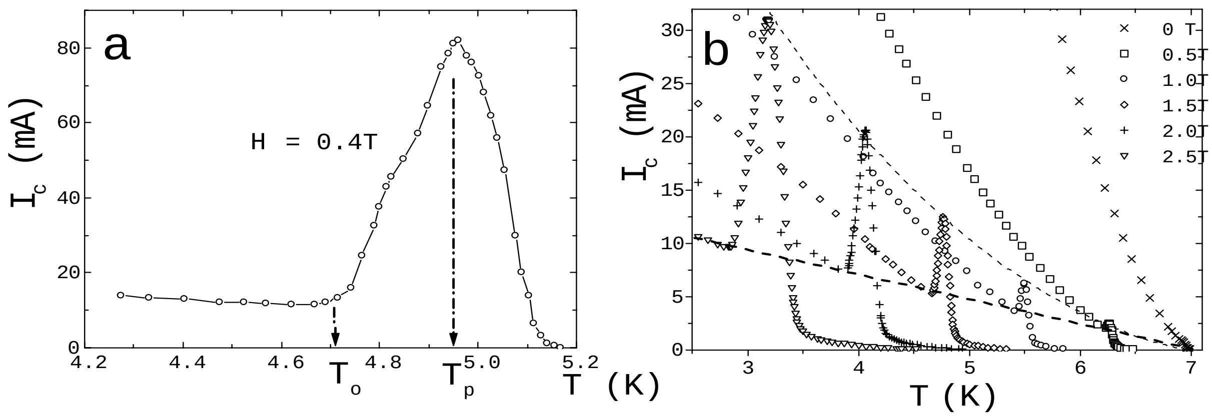

Figure 1. Temperature dependence of critical current showing Peak Effect. (a) Fe doped $NbSe_2$ sample at 0.4T. (b) undoped sample for several fields.

glass, an entangled vortex phase and a Bose glass [3-5]. In addition, for sufficiently weak point disorder, a dislocation-free "Bragg glass" phase is expected [6] that can deform elastically to accommodate the random potential without losing its topological integrity. In experimental situations this Bragg glass is usually referred to as the ordered state. All the glassy phases including the Bragg glass are characterized by a finite depinning current, below which vortices are immobile. This implies that the system remains superconducting even at finite currents, an important consideration in most applications. By contrast, in the liquid phase the vortices are unpinned for any finite current, a fact that reduces significantly the useful range of applications in these materials. Experimental evidence for the vortex liquid and several glassy phases was reported in the High T_c superconductors. In the low T_c superconductor $NbSe_2$ which is the main focus of our work, two vortex phases with finite critical currents were identified, one ordered and the other disordered.

Experimentally several techniques were applied to determine the nature of a vortex state including direct imaging [7,8] and neutron scattering [9]. In the work described here we used fast transport measurements [10,11] because they can provide information on the dynamics of vortex ordering as well as on its static aspects. In the transport experiments the degree of order is inferred from the measured critical current by using the Larkin Ovchinikov [2] criterion according to which the more disordered the vortex lattice the better it can take advantage of the local minima in the pinning potential leading to larger depinning critical currents. In this picture, which was confirmed by simultaneous neutron scattering and transport measurements [12], the critical current density J_c is inversely proportional to the size of a coherent vortex domain.

In standard transport measurements the I-V characteristics are obtained by applying a current ramp and simultaneously measuring the longitudinal voltage drop. The critical current, I_c , is defined as the current value for which the voltage response is above the noise level, typically $< 1\mu V$. Because these are global measurements, the critical current density is usually estimated by assuming a homogenous current distribution. In fact this assumption is often incorrect due to the presence of a surface barrier that leads to current accumulation at the sample edges [13-15] and due to injection of a disordered phase through the sample edges [16].

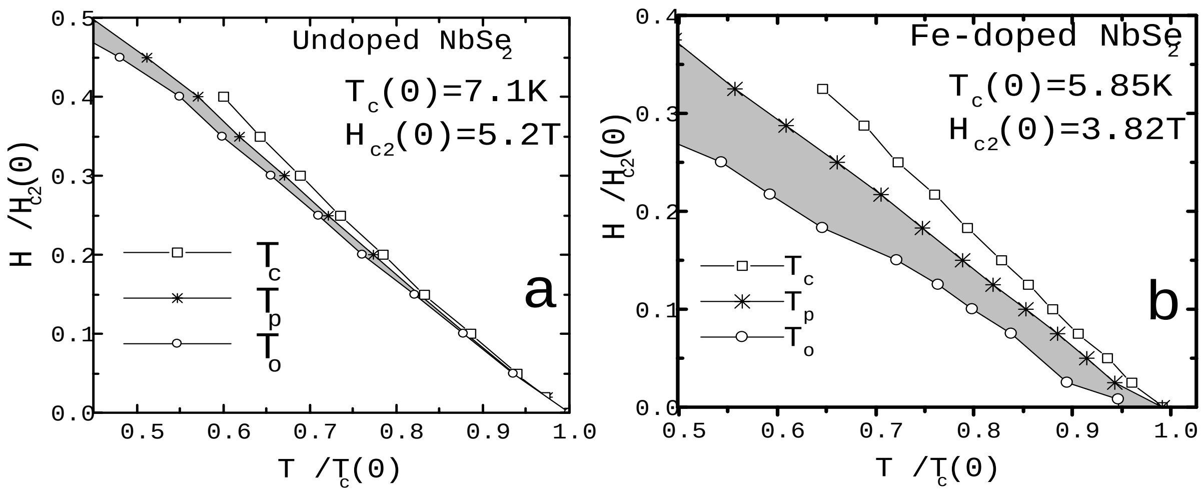

Figure 2. Reduced phase diagram showing the lower peak effect region (shaded area) for (a) undoped sample (b) Fe doped sample.

2. THE PEAK EFFECT

In Fig. 1 we show the temperature dependence of the critical current in two samples, one is undoped clean $NbSe_2$ with $T_c = 7.1K$, and the other containing 200ppm of Fe impurities where $T_c = 5.85K$. The magnetic Fe impurities suppress the superconducting transition while also providing point pinning sites leading to a stronger pinned vortex lattice.

The data in both samples show a "peak effect", whereby the critical current is enhanced significantly just below T_c. A similar peak is seen in the field dependence of the critical current. The peak effect is not unique to $NbSe_2$ but appears to be generic, having been seen in almost every type of weak pinning superconductor [17-21].

Plotting the positions of the peak $T_p(H)$ and the minimum $T_o(H)$ in critical current we obtain a phase diagram, Fig. 2, where the peak effect defines a transition region that separates an ordered vortex state at low fields and temperatures from a disordered phase above it. We note that the transition region is significantly narrower in the undoped sample, Fig. 2a, than in the doped one Fig. 2b. Although we do not have a systematic study yet, it appears that the broadening of the peak with increasing sample disorder is universal.

It is generally accepted that the peak effect is associated with a loss of rigidity in the vortex lattice [2] that is due to the softening of the vortex-vortex interaction relative to the pinning strength close to H_{c2}. But it is not yet clear whether the peak is a crossover between two different regimes of transport or the manifestation of a phase transition between ordered and disordered states. Below we present several recent experimental results in support of a first order transition.

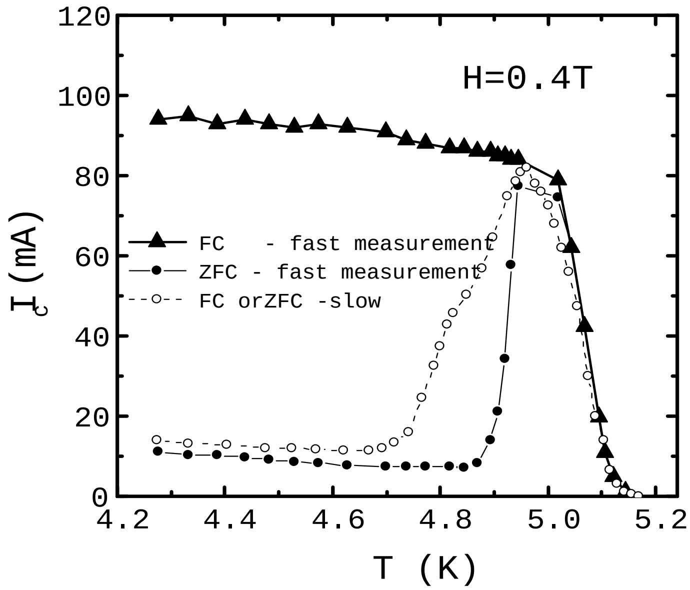

Figure 3. Fast measured critical currents for FC and ZFC states showing metastability [10].

3. METASTABILITY

The presence of pinning centers, in addition to rendering the phase diagram more complex, leads to the existence of metastable states. At low temperatures the vortices become trapped in these long-lived metastable states, making it difficult to uncover the equilibrium phase diagram.

The metastable states give rise to hysteresis and a dependence of the vortex state on its method of preparation. Thus field cooling (FC), whereby the sample is cooled through T_c in the presence of the field results in a vortex state that is more disordered than that obtained by zero field cooling the sample (ZFC) through T_c and then applying the field [17,22,23]. This was initially observed in transport measurements [17] and more recently confirmed by small angle neutron scattering experiments [9,24]. The metastability appears below the peak in critical current $T < T_p(H)$ in both FC and ZFC vortex states. This was demonstrated by using fast current ramps to determine the critical current in the metastable state. Fast measurements are crucial for probing metastable states because, if they are carried out on sufficiently short time scales, they essentially take a snapshot of the instantaneous configuration before the system can reorganize. The relevant time scales can be determined by studying the current sweeping rate dependence of the I-V characteristics [25]. For all the experiments discussed here we found that ramp rates of (200A/s) probe the instantaneous state of the vortex lattice, while slow ramps (0.5A/s) allow vortex reorganization.

Thus by probing the system on short and long time scales we can access both metastable and current driven reorganized states. The results of fast ramp measurements are shown in Fig. 3 for both FC and ZFC states. Applying a current step or a slow current ramp to either the FC or ZFC states results in vortex reorganization into a state with the same critical current. We note the existence of a temperature between T_p and T_c where the vortex state does not depend on its method of preparation and metastability is no longer observed.

4. MOTIONAL ORDERING

The role of an applied current in vortex organization is twofold. For low currents the pinning potential is reduced which leads to vortex de-trapping and enables exploration of the energy landscape. In a sense the current assumes the role played by temperature in ordinary statistical mechanics. For sufficiently high currents when the vortices start flowing the random pinning potential is "smoothed out" which increases the relative importance of vortex-vortex interactions and can lead to an ordered vortex state.

Evidence for motional ordering was seen in transport data [25-27] as well as direct imaging experiments [7]. Based on transport studies, Bhattacharya and Higgins [26] proposed a scenario of a dynamical transition of the moving vortex array, becoming ordered at large velocities. A theoretical justifiaction of this picture was put forward by Koshelev and Vinokour [28] who pointed out the analogy between thermal fluctuations and driving current. They argued that the random potential that leads to a disordered state in the stationary vortex array appears as a temporally fluctuating Langevin force in the moving vortex reference frame.

Motional ordering due to smoothing of the random poential at high velocities could explain the difference between the ZFC and the FC vortex states. In the ZFC method of preparation the superconducting state is prepared in the absence of magnetic field. When subsequently the field is applied, large screening currents flowing at the sample edges drive vortices across the sample boundaries into its interior. In most experiments the field is ramped up from zero at relatively high ramping rates resulting in large vortex penetration velocities. This leads to motional ordering of the incoming vortices which is manifest in the observed higher degree of order in the ZFC state. In the FC case the magnetic flux uniformly permeates the sample when the field is applied in the normal state. Here the vortices start forming inside the sample from the already existing flux when the temperature is lowered below T_c. In this method of preparation the vortex system is formed in the region of phase diagram where the disordered state is stable[29]. Further cooling results in a supercooled disordered phase [20].

5. CURRENT DRIVEN ORGANIZATION FOR $T < T_o$

For $T < T_o$ the FC state is metastable. The annealed stable state can be reached by applying an external perturbation such as mechanical shaking or passing a current [20,30]. Surprisingly the FC state undergoes a transition to the stable ordered state even when driven with a current that is significantly lower than its critical current. To understand this phenomenon we used fast transport measurements to follow the response of the FC vortex lattice to sub-critical driving currents. The experiments consisted of applying a current step to the pristine FC state and monitoring the

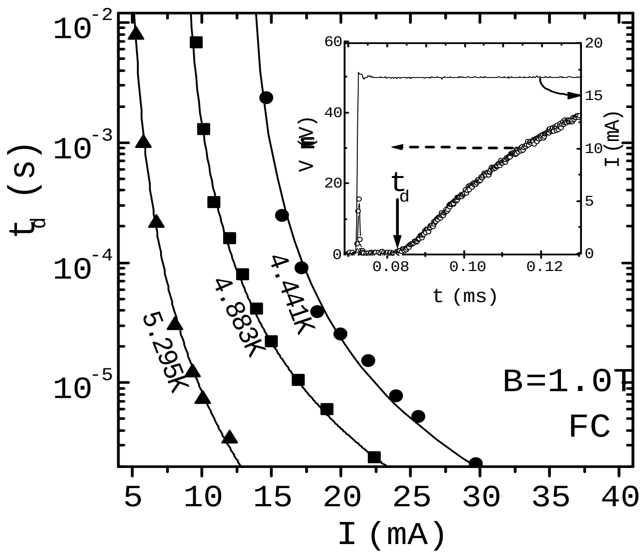

Figure 4. Temperature and current dependence of delay time t_d [30]. Inset: temporal evolution of FC state response to current step illustrating how delay time is measured.

temporal evolution of the voltage response[30]. A typical result is shown in the insert of Fig. 4. We found that the response consists of two distinct regimes. The first is a waiting time t_d during which no measurable voltage response is observed. Subsequently the response starts growing from zero with a characteristic time scale $\tau \gg t_d$ until it saturates at a value corresponding to the response of the ordered phase.

One of the key questions here is what are the vortices doing during t_d. Are they just "waiting" as would be the case for thermal activation or tunneling, or are they performing small movements leading to global reorganiztion, which are not detectable with our transport measurements. From the transport experiments we were able to obtain a number of clues:

a. The vortex state is changing during t_d albeit through movements that are too small to produce a voltage signal. This was verified by showing that t_d is additive: if the current is interrupted at a time $t_o < t_d$, and then reapplied later the delay time before a voltage response appears is not td , as one would expect for thermal activation or tunneling, but rather $t_d - t_o$.

b. The vortex rearrangements during t_d are irreversible. We verified this by interrupting the current as described above, at a time $t_o < t_d$, and then reapplying a current of the same amplitude but *opposite* polarity. The delay time was still $t_d - t_o$. indicating that reversing the current does not *undo* the rearrangements that already took place.

c. The delay time is strongly dependent on driving current and temperature. This is shown in Fig. 4 where we note that t_d. can change by up to five decades for a twofold change in current amplitude.

Based on these results we propose a scenario for the metastable to stable transition in the vortex state. According to the Bean critical state model [31] a sub-critical current penetrates the sample from the edges flowing with a current density that must be equal to the local critical value. Thus when a sub-critical current $I < I_c$ is applied to the FC state it initially flows along each edge within a strip taking up

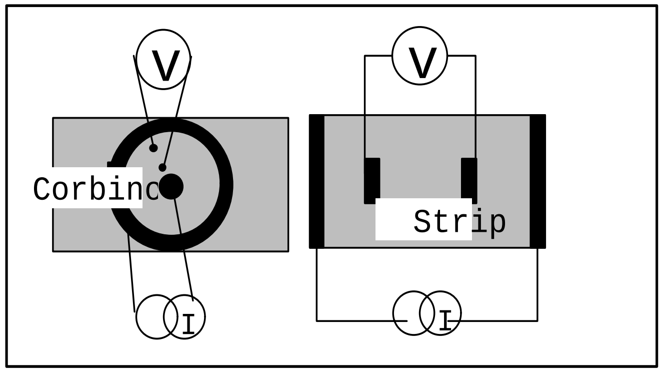

Figure 5. Lead configuration in a) Corbino geometry; b) strip geometry.

a fraction I/I_c of the sample width and carrying the critical current density of the disordered state, J_c. Within the regions where the current penetrates, it facilitates local rearrangements of disordered vortices. This allows further current penetration into the sample, which leads to yet more ordered regions and so on. Eventually, after a delay time t_d., the current carrying region forms a contiguous path connecting the sample edges. Since all the vortices along this path are driven at their respective critical current density they can start moving and traverse the sample continuously giving rise to the first detectable voltage signal. Numerical simulations show that the measured temperature and current dependence of t_d are in excellent agreement with predictions based on this model [32].

6. EFFECT OF BOUNDARIES

In the lower part of the peak region, $T_o < T < T_p$, the results are sensitively dependent on the geometry of the boundaries.

For a strip geometry, Fig 5b, we find pronounced metastabilities. Applying a slow dc current to either the FC or ZFC states results in the same critical current which is intermediate between the fast measured values of the two states (see Fig 3). As before we can follow the vortex reorganization in the ZFC state by applying a current step and monitoring the voltage response. A measurable response is only seen for current amplitudes exceeding the ZFC critical current, I_o. The initial response is as expected for a system with critical current I_o. As time progresses however the response diminishes [10], Fig. 6a, indicating an increase in critical current associated with penetration of a disordered phase from the sample edges [16,29]. As shown in Fig. 6b, this can be seen directly by measuring the critical currents at various times during this evolution with a fast current ramp.

The results are strikingly different if the the boundaries are excluded from the measurement by using a Corbino geometry, Fig5a, or by successively cutting the sample and subtracting the edge effects. In this case the ZFC state appears to be stable and ordered regardless of the measurement speed!

The difference between the two lead configuration is due to the fact that the vortex motion is normal to the applied current. Accordingly in the case of the strip configuration the vortices enter and exit through the sample edges. By contrast in

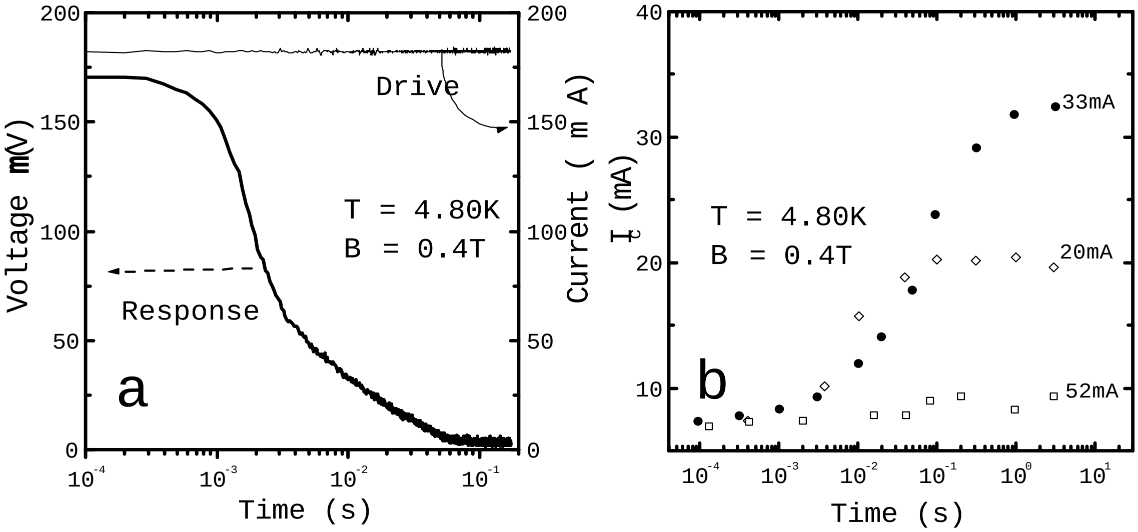

Figure 6. Response of ZFC state to a dc current step [10]. a) Time dependence of response. b) Evolution of critical current during steps of various amplitudes.

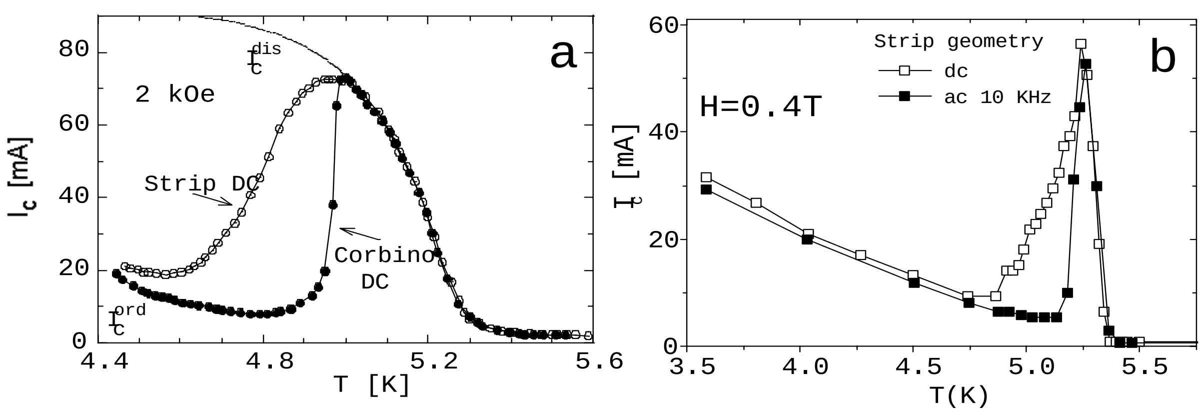

Figure 7. a)Effect of boundaries on critical current illustrated by comparing strip to Corbino geometry in same sample [29]. b) Effect of finite frequency current on the peak is similar to that of eliminating the boundaries[33].

the Corbino geometry the radial current injection leads to azimuthal vortex flow that does not entail crossing sample boundaries. In Fig.7a we compare the results obtained in the same sample for these two geometries[29]. The broad peak in the critical current of the ZFC state measured in the strip geometry is transformed into a sharp jump in the Corbino configuration. This sharp jump is robust and independent of measurement speed. In addition the Corbino geometry revealed a new jump in I_c at low fields and temperatures which was not seen by other transport techniques. The main difference between these configurations is in the boundaries. Vortices that are injected into the sample through the surface barrier at the edge enter in a disordered states due to irregularities in the barrier height. The elimination of edge crossing in the Corbino geometry suggests that the jump in critical current at T_p is a bulk phenomenon.

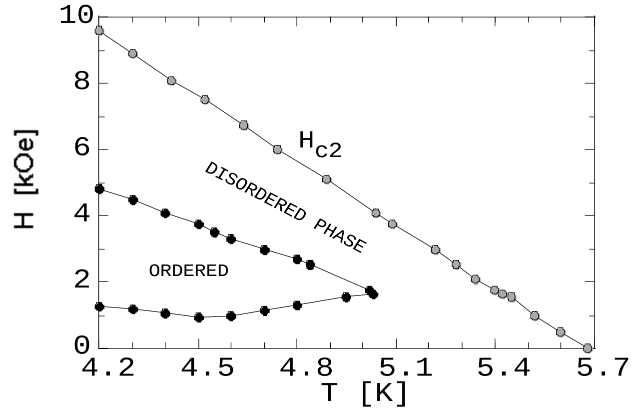

Figure 8. Phase diagram obtained from jump in critical current in Corbino geometry [29].

The sharpening of the peak for the ZFC vortex state can also be observed in a strip geometry if the effects of edge injection of disordered phase are eliminated. This was done by a number of techniques: fast measurements[10] Fig. 3, high frequency ac measurements [11,16,29,33] Fig. 6b and slow dc measurements when the effect of the boundaries is subtracted by successively cutting the sample to reduce its width [34]. In each of these cases the effects of boundary crossing are eliminated giving access to the dynamics of the vortices in the bulk because the penetration of disordered phase from the edge is governed by a finite relaxation time [16]. Measurements on shorter time scales cannot capture the effects associated with edge contamination. Subtracting the edge effect by separating bulk from edge contributions to I_c gives again the same result. In the Corbino geometry two jumps in critical current are seen by reducing the field at fixed temperature. The first is a jump to a lower critical current indicating the formation of an ordered state while the second is a jump to a higher critical current signaling the reentrance of the disordered state at low fields. The reentrance of the disordered state was previously reported in susceptibility measurements [35]. By plotting the locus of the two jumps one obtains a phase diagram that contains an ordered phase at intermediate fields enclosed by a disordered phase at high and low fields, Fig. 8. This phase diagram is consistent with theoretical suggestions [6].

7. CONCLUSIONS

The experimental results on the peak effect can be summarized as follows:

a) The peak regime is narrowest in the cleanest samples and broadens with increasing defects or impurities.

b) The shape of the peak depends on the speed of measurement. In an ac measurement it becomes sharper with increasing frequency becoming almost an abrupt jump at the highest frequencies. It is equally sharp in a fast DC measurement on a ZFC vortex state.

c) The shape of the peak depends on the geometry of the boundaries. It can be made very sharp, almost a jump (sharper than the width of the superconducting transition) by excluding the boundaries from the measurement.

Based on these results we argue that the peak effect is a manifestation of a first order transition between an ordered Bragg glass and a disordered vortex glass. This transition, as measured by excluding edge contamination, is intrinsically quite sharp. The broadening observed in the strip geometry by slow dc measurements is due the injection of disordered phase through the surface barrier at the edges leading to a higher value of the global I_c. This picture is consistent with local Hall probe measurements[15,16] which demonstrated the presence of current injected disordered strips at the sample edges in a strip geometry. Recent imaging experiments using a variant of Hall microscopy [36] show that as the vortex lattice is heated through the peak effect region the disordered phase appears to be moving in from the edge in general agreement with this picture.

In summary, the experiments described here show that material disorder and sample boundaries play a crucial role in the vortex phase diagram and dynamics. Due to material disorder the system can become trapped in metastable states preventing it from attaining equilibrium. An external current has two competing effects: a dynamic injection of a metastable disordered phase through the sample edges and the annealing of the metastable phase in the bulk. By carrying out experiments that exclude the sample boundaries we have shown that the peak effect sharpens into a jump supporting the interpretation of the peak in terms of a first order phase transition between ordered and disordered vortex states.

ACKNOWLEDGMENTS

E. Y. A. wishes to acknowledge support from NSF and DOE.

EZ acknowledges support from the German-Israeli Foundation G.I.F. and the US-Israel Binational Science Foundation BSF

REFERENCES

[1] D.R. Nelson, Phys. Rev. Lett. **60**, 1973 (1988) .

[2] A.I. Larkin and Yu. N Ovchinnikov, J. Low Temp. Phys, **B 32** , 409 (1979).

[3] Nelson D. R. and Le Doussal P., Phys. Rev. **B 42** , 10113 (1990).

[4] D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. **B 43** , 130 (1991).

[5] G. Blatter et al. Rev. Mod. Phys. **66**, 1125 (1994).

[6] T. Giamarchi and P. Le Doussal, Phys. Rev. Lett. **72**, 1530, (1994); Phys. Rev. **B 52** , 1242 (1995).

[7] F. Pardo, et al. Nature **396**, 348 (1998).

[8] M. Marchevsky et al. Phys. Rev. Lett. **78**, 531 (1997).

[9] U. Yaron et al. Nature **376**, 753 (1995).

[10] Z.L. Xiao, E.Y. Andrei and M. Higgins, Phys. Rev. Lett, **83**, 1664 (1999).

[11] E.Y. Andrei, Z.L. Xiao, P. Shuk and M. Greenblatt, J. Phys IV, Pr10, 5 (1999).

[12] P. L. Gammel et al. Phys. Rev. Lett. **80**, 833 (1998).

[13] C.P. Bean and J.D. Livingston, Phys. Rev. Lett. **12**, 14, (1964).

[14] E. Zeldov et al. Phys. Rev. Lett. **73**, 1428, (1994).

[15] Y. Paltiel et al. Phys. Rev. **B 58** , R14763 (1998).

[16] Y. Paltiel et al. Nature **403**, 398 (2000).

[17] P. H. Kes and C. C. Tsuei, Phys. Rev. **B 28** , 5126 (1983); R. Wordenweber, P. H. Kes and C. C Tsuei, Phys. Rev. **B 33** , 3172 (1986).

[18] W. K. Kwok, et al. Phys. Rev. Lett. **73**, 2614 (1994).

[19] M. Higgins and S. Bhattacharya, Physica C **257**, 233 (1996).

[20] W. Henderson, E.Y. Andrei, M.J.Higgins, and S. Bhattacharya, Phys. Rev. Lett. **77**, 2077 (1996).

[21] X. S. Ling, J. I. Budnick, and B. W. Veal, Physica C **282**, 2191 (1997).

[22] B. Sas, et al Phys. Rev. B 61, 9118 (2000).

[23] S.O. Valenzuela and V. Bekeris, Phys. Rev. Lett. **84**, 4200 (2000).

[24] X. S. Ling Phys. Rev. Lett. **86**, 712 (2001).

[25] Z. L. Xiao, E. Y. Andrei, P. Shuk and M. Greenblatt, Phys. Rev. Lett. **85**, 3265 (2000).

[26] S. Bhattacharya and M. J. Higgins, Phys. Rev. Lett. **70**, 2617 (1993).

[27] M. C. Hellerqvist et al. Phys. Rev. Lett. **76**, 4022 (1996).

[28] A. E. Koshelev and V. M. Vinokur, Phys. Rev. Lett. **73**, 3580 (1994).

[29] Y. Paltiel et al. Phys. Rev. Lett. **85**, 3712 (2000).

[30] Z. L. Xiao, E. Y. Andrei, P. Shuk and M. Greenblatt, Phys. Rev. Lett. **86**, 1753 (2001)

[31] C.P. Bean, Phys. Rev. Lett **8**, 250 (1962)

[32] E.Y. Andrei et al to be published.

[33] W. Henderson, E.Y. Andrei and M. Higgins, Phys. Rev. Lett. **81**, 2352, (1998)

[34] Z.L. Xiao et al. To be published.

[35] K. Ghosh *et al*, Phys. Rev. Lett. **60**, 1973, (1988); S.S. Banerjee *et al*, J. Phys. Soc. Jap. Suppl. **69**, 262 (2000).

[36] M. Marchevsky, M. J. Higgins and S. Bhattacharya, Nature **409**, 591(2001)