Onset of Motion and Dynamic Reordering of a Vortex Lattice

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Time resolved transport measurements on a driven vortex lattice in an undoped $2H$-$NbSe_2$ crystal show that the response to a current pulse is governed by healing of defects as the lattice evolves from a stationary to a moving steady state and that the response time reflects the degree of order in the initial vortex state. We find that stationary field cooled vortex lattices become more ordered with decreasing temperature and identify a temperature below which a qualitative change in the response signals the disappearance of topological defects.

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In the presence of random pinning, the crystalline long-range order of vortex lattices in superconductors is lost [1,2]. However, if pinning is sufficiently weak, remnants of the long-range order are expected to survive, giving rise at low temperatures to a topologically ordered state [3,4], the Bragg glass, which is separated from the high temperature disordered phase by a first order transition. Crossing this transition line often results in a heterogeneous state consisting of ordered and disordered domains, which give rise to a range of interesting history effects and nonlinear dynamics [5–7]. These heterogeneous states can be formed anywhere below the spinodal point [8,9]—the temperature above which ordered domains cannot exist. Experiments probing the degree of order of the vortex lattice below the spinodal point have shown that it is quite sensitive to the way in which the lattice was prepared. In particular, it was found that, if the vortex lattice is set in motion during the preparation, whether by applying a current, by changing the field (as in zero field cooling), or by shaking, the lattice becomes more ordered [5,6,10–13]. These phenomena illustrate some enduring puzzles in vortex physics which this Letter will address: dynamic reordering at the onset of motion [14,15], its dependence on the initial state, and the mechanisms of defect healing.

Here we present time resolved transport experiments investigating the onset of motion of vortex lattices prepared without any dynamic perturbations in a weak pinning $NbSe_2$ sample. Below the spinodal line we find that, when set in motion, all lattices evolve into a more ordered state over a characteristic time scale, which depends on the degree of order of the initial stationary lattice. Moreover, we find that a stationary field cooled (FC) lattice becomes more ordered with decreasing temperature and that at the lowest temperatures topological defects become scarce or absent, consistent with the formation of a Bragg glass. At higher temperatures, a sharp change in the reordering time scales, strong hysteresis, and plastic response reflect the proliferation of topological defects as a precursor of the transition to a disordered state.

Measurements were carried out on an undoped single crystal of $2H$-$NbSe_2$ with dimensions $4.41\ \mathrm{mm} \times 0.83\ \mathrm{mm} \times 6\ \mu\mathrm{m}$, transition temperature $T_c = 7.2$ K, and width 130 mK. The magnetic field was along the c axis, and the currents were in the a-b plane. Pulsed measurements were carried out with a four probe technique [5] and an external controller, ADwin-Gold, for fast data acquisition and deep memory. The high level measurements ($V \geq 5\ \mu$V) employed a low noise ($4\ \mathrm{nV/Hz^{1/2}}$) fast amplifier with 2 μs time resolution. For the low-level data, we used a nanovoltmeter (45 ms resolution). The static vortex states were freshly prepared before every measurement. In the FC procedure, the sample was first warmed to 10 K and then cooled slowly (over ~5 min) to the measurement temperature T^m. The field-cooled-warm (FCW) states were prepared by first field-cooling to 4.25 K and, subsequently, slowly heating to T^m.

Because FC states are often metastable, measurements of the V-I curves depend on the current ramping rate [6,8]. Nevertheless, it is still possible to extract rate-independent results from the V-I data by first annealing the vortex lattice with a large enough current or, equivalently, by using a slow current ramp [5]. A typical curve obtained by this procedure at 4.90 K and 0.2 T is plotted in the inset in Fig. 1(a). The main panel illustrates the temperature dependence of the critical current obtained with a 1 μV criterion and shows a small peak at 6.60 K (the peak effect) usually associated with the order-disorder transition [16,17]. According to the Larkin-Ovchinnikov model [18], the bulk critical current density is a measure of vortex lattice order. Thus, if the current density were uniform, it would be possible to extract the degree of order from the measured critical currents. But this is usually not the case, especially for clean samples where, due to the surface barrier, most of the current flows on sample edges [19,20]. In this Letter, instead of focusing on the critical current, we measure the vortex lattice response to a current pulse as it evolves from a stationary to a moving steady state with a given saturation voltage V_0. In practice, we

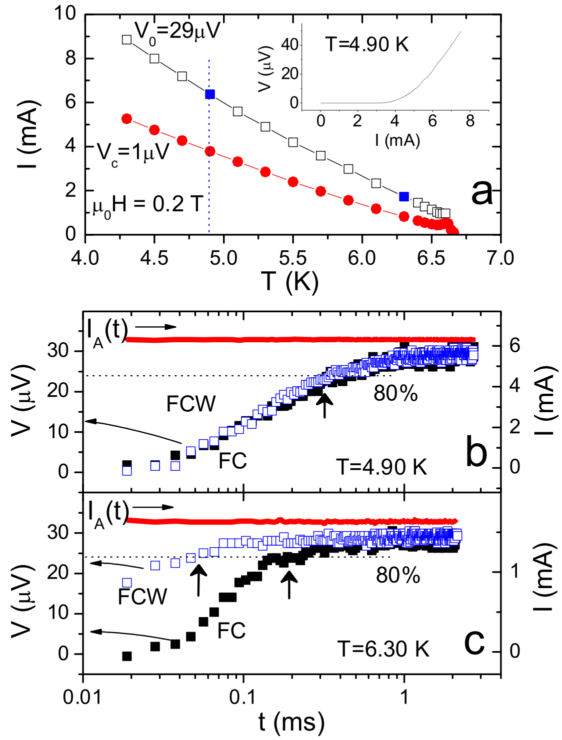

FIG. 1 (color online). (a) Temperature dependence of critical current defined by a 1 μV criterion (solid circles) showing the peak effect at 6.60 K. Open squares: current values corresponding to a saturation voltage $V_0 = 29\ \mu$V. Inset: V-I curve obtained with slow current ramp. The two solid squares mark the levels of the current pulses in (b) and (c). (b) Onset of motion as monitored by evolution of the voltage response to a current pulse of fixed amplitude $I_A = 6.3$ mA (solid line) at 4.90 K for $V_0 = 29\ \mu$V. Solid squares, FC state; open squares, FCW state. (c) Same as (b) at 6.30 K. Note that here $I_A = 1.63$ mA. Vertical arrows show the definition of τ_{80}.

monitor the evolution of the response while holding the current at a fixed level. In order to compare different vortex states, we choose the level of the applied current so as to maintain the same value of V_0. In Fig. 1(a), we show the temperature dependence of the current amplitude required to maintain $V_0 = 29\ \mu$V. This procedure naturally eliminates the dependence on surface currents because the final vortex velocity v, which depends only on the bulk current density J and the applied field B, is kept constant ($V_0 = vBl \propto J$, where l is the distance between voltage leads). Typical response curves are shown in Figs. 1(b) and 1(c), where we compare the evolution of the response corresponding to $V_0 = 29\ \mu$V for FC and FCW lattices at two temperatures, 4.90 and 6.30 K. The characteristic response times in the vortex state, τ_{80}, defined as the time to reach 80% of V_0, are much longer than the response time $\sim 2\ \mu$s measured in the absence of vortices. Heating due to vortex motion can be ruled out, because the thermal response time in our setup is much longer (~ 50 ms) and also because the response for identical measurement conditions becomes significantly shorter if the vortex lattice is prepared in the presence of an external drive.

The response time reflects the dynamic reordering of the vortex lattice from a stationary to a moving steady state. Therefore, it must depend on the measurement conditions: V_0 and temperature T^m, as well as on the initial degree of order of the lattice, which is determined by the preparation temperature T^e. We found that, by keeping V_0 and T^m fixed and varying T^e, effects due to the initial degree of order can be separated from those due to measurement conditions. Two initial states were compared: the FC lattice, where $T^e = T^m$, and the FCW lattice, with $T^e = 4.25\ \mathrm{K} \neq T^m$. The results for $V_0 = 29\ \mu$V and $T^m = 6.30$ K are shown in Fig. 1(c). Despite the identical measurement conditions, the response of the two lattices is strikingly dissimilar and, therefore, must reflect the different degrees of order of the two initial stationary lattices. It is known from small angle neutron scattering (SANS) experiments [13] that the FCW lattice is more ordered than the FC lattice. We, therefore, conclude that the degree of order of the vortex lattice is reflected in the values of τ_{80} and that, if T^m and V_0 are the same, then shorter τ_{80} correspond to more ordered lattices. The shorter τ_{80} of the FCW lattice in Fig. 1(c) demonstrates that the FC lattice continues to become more ordered as the temperature is reduced down to 4.25 K and that the ordered structure of the low temperature lattice is maintained upon reheating back up to 6.30 K. The experiments were repeated for a series of values of T^m and V_0.

In Fig. 2(a), we plot τ_{80} at $V_0 = 29\ \mu$V for FC and FCW states as a function of T^m. Thermal hysteresis is clearly seen above $T_L \sim 5.70$ K. The error bar in the low-level data ($V_0 = 1\ \mu$V) shown in Fig. 2(b) were obtained by averaging over 10 repeated runs to reduce the error bar associated with the lower time resolution (45 ms). Note the longer time scales in the 1 μV data, reflecting a significant slowdown of the reorganization process at low driving levels [5]. The low-level response is not smooth, it develops steps, and the voltage onset following the application of the current appears only after a certain delay time [5]. These data exhibit other features characteristic of plastic response and are reported elsewhere [21].

Interestingly, in spite of the pronounced differences between the high-level and low-level data, the value of T_L marking the onset of hysteresis is independent of V_0. This could be interpreted in terms of one of several scenarios: (1) All vortex states formed at $T < T_L$ are identical. This would be the case if, below this temperature, thermal fluctuations are too weak to allow phase space exploration, resulting in a supercooled replica of the state at T_L. (2) Below T_L, the vortex lattices are not all identical, but excursions in temperature are reversible. (3) Below T_L, FC and FCW vortex lattices are not identical, and temperature excursions are irreversible, but the difference is not reflected in the values of τ_{80}. The latter would be the case if the onset of motion at low temperatures becomes less sensitive to the degree of order of the initial vortex lattice.

To distinguish between the proposed scenarios, we carried out an experiment where FC lattices prepared at different T^e were compared by warming them all up to the same

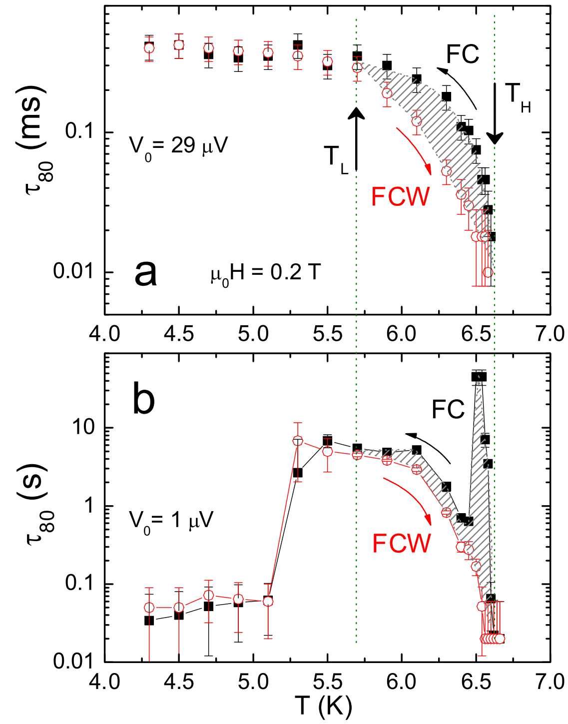

FIG. 2 (color online). (a) Temperature dependence of τ_{80} at $V_0 = 29\ \mu$V for FC and FCW states showing the position of T_L and of T_H. (b) Temperature dependence of τ_{80} at $V_0 = 1\ \mu$V. The position of T_L and T_H is the same as in (a).

$T^m = 6.56$ K, where the evolution of the $V_0 = 1\ \mu$V response was monitored. With this procedure, referred to as FC-cool-warm (FC-CW), the response times directly reflect the differences in the degree of order of FC states prepared at different T^e. (The FC-CW is similar to the FCW procedure, except that in the FCW case $T^e = 4.25$ K is constant and T^m is varied.) The results are shown in Fig. 3(b) (we employed τ_{90}, the time to reach 90% of V_0 because of the lower time resolution in the low-level measurements). The value $T^m = 6.56$ K was chosen to maximize the contrast between the response times, because at this temperature the FCW response is still smooth and relatively fast, while the FC response is much slower with strong evidence of plasticity including steps as illustrated in Fig. 3(a). Thus, if supercooling occurred for $T < T_L$, the value of τ_{90} in the FC-CW state would saturate below T_L. In fact, as shown in Fig. 3(b), no saturation occurs down to the lowest temperatures. This clearly rules out both supercooling (scenario 1) and the reversible temperature excursions (scenario 2). Rather, the data support scenario 3 by showing that the FC and FCW states are, in fact, not identical. This is because if, at any temperature $T^* > 4.25$ K, the FC and FCW states were identical, the response time of the FC-CW state prepared at $T^e = T^*$ would be the same as that prepared at $T^e = 4.25$ K, contrary to what is observed. Clearly, the vortex state continues to change for $T < T_L$. Moreover, these data show that the change is irreversible, because if we consider, for example, the response time of the lattice prepared at $T^e = 4.25$ K, it is shorter than that of the higher temperature lattices even though the lattice was warmed through all higher temperatures before being measured. This demonstrates that the healing of defects during cooling is stable and that (on the measurement time scale) they do not reappear upon heating back to 6.56 K. In other words, the lowest temperature remains encoded in the degree of lattice order and can be retrieved at T^m from the superheated lattice by applying a current pulse.

A similar method was employed for superheated lattices. The procedure, FCW-warm-cold (FCW-WC), was initiated by preparing an FCW lattice at a target temperature T^e (where $T^e > T^m = 6.56$ K) followed by cooling back to 6.56 K, where τ_{90} corresponding to $V_0 = 1\ \mu$V was measured. The data are shown in Fig. 3(c). We note that the response saturates to the FC value at $T_H = 6.64$ K, indicating the limit of superheating of the ordered vortex lattice that can be obtained with this procedure. This value is consistent with the somewhat higher spinodal temperature which can be measured directly only by employing a more elaborate method [8].

The significance of T_L is best illustrated by considering the response of the FC-CW lattice shown in Fig. 3(b). Because the measurement conditions are identical, the variation in τ reflects the difference in defect concentration

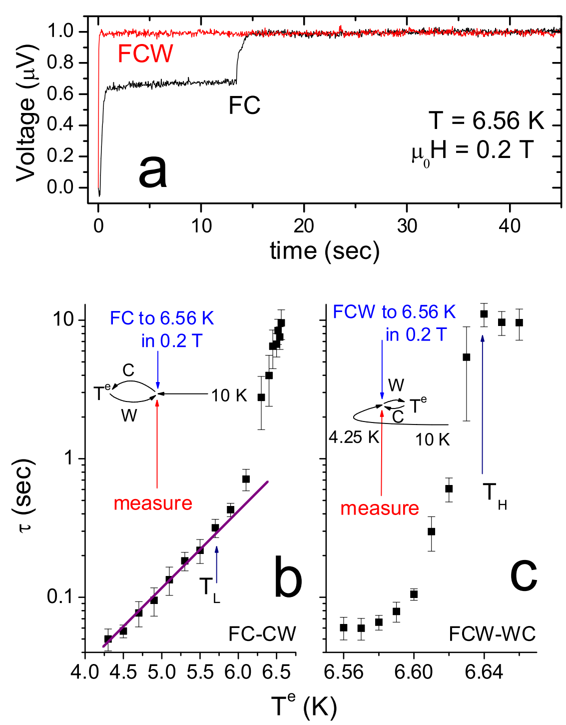

FIG. 3 (color online). (a) Time evolution of response to current pulse measured at $T^m = 6.56$ K and $V_0 = 1\ \mu$V for FC and FCW lattices. (b) Response times for FC-CW lattices as a function of preparation temperature T^e, illustrating the definition of T_L. The preparation sequence, described in the text, is schematically sketched. The solid line represents a fit to the data as discussed in the text. (c) Response times for FCW-WC, illustrating the definition of T_H.

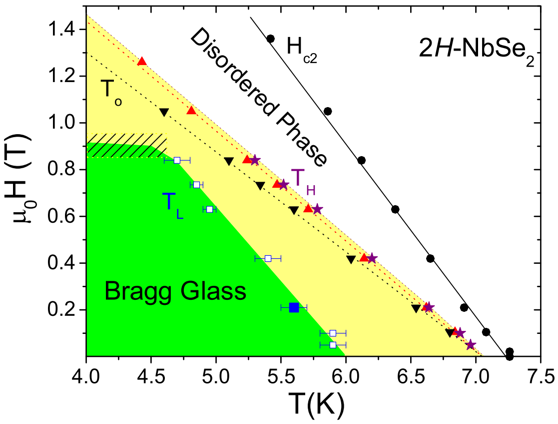

FIG. 4 (color online). *H-T* phase diagram showing the line T_L (squares), below which topological defects become scarce, and T_H (stars) the limit of superheating of the Bragg glass. Also shown are T_o (inverted triangles) and T_p (triangle), representing the onset and peak of the peak effect. No data is available for the hashed area.

for lattices prepared at different T^e. For $T^e < T_L$, the defect healing rates can be fit by $\tau_{90}^{-1} \propto \tau_1^{-1} \exp(-\alpha_1(T^e))$, suggesting an activated process with a T^e dependent barrier, $\alpha_1(T^e) = 1.2T^e$, and an attempt frequency $\tau_1^{-1} = 4 \times 10^3\ \mathrm{s}^{-1}$. The reduction in barrier height with decreasing T^e is consistent with strengthening vortex-vortex interactions compared to pinning at lower temperatures. This can also explain the fact that the lattice continues to reorder in spite of diminishing thermal fluctuations. In this picture, the sharp break in slope at T_L indicates the appearance and proliferation of another type of defect for which healing is much slower. It is important to note that T_L coincides with the appearance of steps in the time evolution of the response. Such steps are attributed to plastic flow and to the appearance of topological defects such as dislocations. The disappearance of topological defects below T_L is also consistent with the expected formation of a low temperature Bragg glass. This was shown to be the case by SANS experiments on the FC vortex lattice in high purity Nb samples [13,22].

In the *H-T* phase diagram shown in Fig. 4, the $T_L(H, T)$ data demarcates the boundary of the dislocation free lattice. The value of T_L at 0.2 T (solid square) indicates the point that was obtained by the FC-CW procedure described above. At other fields (open squares), T_L was defined by the disappearance of hysteresis in the FC and FCW procedures. Recent experiments in the high T_c superconductor LaSrCuO provide evidence for a transition from a Bragg glass to a more disordered vortex glass with increasing field [23]. This is qualitatively consistent with the loss of the T_L line indicated by the hashed area in the figure (but it could also be due to the lower sensitivity at high fields).

In summary, the experiments described here demonstrate that the response time of a vortex lattice to a current pulse reflects the healing of defects at the onset of motion. For sufficiently weak pinning, defects heal as the temperature is reduced, even without external drive until a temperature is reached, T_L, below which topological defects are scarce or absent. For $T > T_L$, defects proliferate, leading to a substantial slowdown in the onset of motion, to plastic response and to history effects. This is in contrast to earlier experiments in "dirty" Fe doped $NbSe_2$ [5] where, because of much stronger pinning, the FC vortex lattice freezes in a supercooled disordered state and no ordering is observed unless the lattice is set in motion.

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[1] A. I. Larkin, Sov. Phys. JETP **31**, 784 (1970).
[2] Y. Imry and S. K. Ma, Phys. Rev. Lett. **35**, 1399 (1975).
[3] T. Nattermann, Phys. Rev. Lett. **64**, 2454 (1990).
[4] T. Giamarchi and P. LeDoussal, Phys. Rev. Lett. **72**, 1530 (1994).
[5] W. Henderson, E. Y. Andrei, M. J. Higgins, and S. Bhattacharya, Phys. Rev. Lett. **77**, 2077 (1996).
[6] E. Y. Andrei *et al.*, J. Phys. IV **9**, 5 (1999).
[7] F. Portier *et al.*, Phys. Rev. B **66**, 140511(R) (2002).
[8] Z. L. Xiao, O. Dogru, E. Y. Andrei, P. Shuk, and M. Greenblatt, Phys. Rev. Lett. **92**, 227004 (2004).
[9] D. Li and B. Rosenstein, Phys. Rev. B **65**, 220504(R) (2002).
[10] P. Thorel *et al.*, J. Phys. (Paris) **34**, 447 (1973).
[11] U. Yaron *et al.*, Phys. Rev. Lett. **73**, 2748 (1994).
[12] N. Avraham *et al.*, Nature (London) **411**, 451 (2001).
[13] X. S. Ling *et al.*, Phys. Rev. Lett. **86**, 712 (2001).
[14] L. Balents, M. C. Marchetti, and L. Radzihovsky, Phys. Rev. B **57**, 7705 (1998).
[15] C. J. Olson, C. Reichhardt, and F. Nori, Phys. Rev. Lett. **81**, 3757 (1998).
[16] M. J. Higgins and S. Bhattacharya, Physica (Amsterdam) **257C**, 232 (1996).
[17] G. P. Mikitik and E. H. Brandt, Phys. Rev. B **64**, 184514 (2001).
[18] A. I. Larkin and Y. N. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).
[19] Y. Paltiel *et al.*, Phys. Rev. Lett. **85**, 3712 (2000).
[20] Z. L. Xiao *et al.*, Phys. Rev. B **65**, 094511 (2002).
[21] G. Li *et al.*, J. Phys. IV **131**, 101 (2005).
[22] E. M. Forgan *et al.*, Phys. Rev. Lett. **88**, 167003 (2002).
[23] U. Divakar *et al.*, Phys. Rev. Lett. **92**, 237004 (2004).