Metastability and Glassy Behavior of a Driven Flux-Line Lattice

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Strong metastability and history dependence are observed in dc and pulsed transport studies of flux-line lattices in $2H$-NbSe$_2$, leading to the identification of two distinct states of the lattice with different spatial ordering. The metastability is most pronounced upon crossing a transition line marked by a large jump in the critical current (the peak effect). Current-induced annealing of the metastable state towards the stable state is observed with a strongly current dependent annealing time, which diverges as a threshold current is approached from above. [S0031-9007(96)01054-X]

In the absence of disorder the physics of a magnetic flux-line lattice (FLL) is governed by the interplay between thermal fluctuations, which favor melting, and interactions, that lead to ordering. The resulting phase diagram consists of a liquid and a solid phase with relatively simple dynamics. Quenched disorder causes the system to develop additional phases and complex dynamic effects such as pinning and irreversibility in the magnetic and electric responses. The role played by disorder and pinning in the physics of FLL in equilibrium has recently become an area of intense study [1,2]. A related but distinct topic of current interest concerns the role of motion on the spatial ordering of the FLL, the resulting dynamical transitions or crossovers that may occur, and the relation they bear to the disorder free situation [3–7].

In this Letter we report on the existence of two distinct states of the FLL, one disordered, the other much less disordered (hereafter referred to as the ordered state), with strikingly large differences between their transport properties. As a result, the system displays a wide range of phenomena such as history dependence, metastability, current-induced annealing, and glassy relaxation. Each of these states is stable in its own sharply defined region of the (H, T) plane and metastable elsewhere, and each can be accessed with a simple reproducible procedure. Our experiments show directly that the metastable state can be annealed into the "equilibrium" state by applying a current that depins the FLL. The annealing kinetics is found to be strongly current dependent, with the annealing time diverging as the depinning current is approached from above. The variation of these phenomena with field, temperature, and driving current provides direct access to the interplay between static and dynamic transitions and can elucidate the role of disorder in different parts of the FLL phase diagram. Our results can also be used to interpret the rich and complex history dependence studied earlier in low T_c superconducting films [8,9].

The history dependence is closely associated with the phenomenon of "peak effect." This effect, which is observed in many weak-pinning superconductors, is characterized by a sudden enhancement of the critical current just below $H_{c2}(T)$ and is readily observed [4] as a function of H or T. It reflects the rapid softening of the elastic moduli of the flux lattice as $H_{c2}(T)$ is approached, which allows pinning sites to distort the lattice more strongly, leading to a sharp rise in the critical current. This is described in the Larkin-Ovchinnikov (LO) collective pinning model [10] as a reduction in a correlation volume V_c which is the characteristic size over which the FLL is ordered. In this model the critical current density is given by $J_c = B^{-1}(n_p \langle f^2 \rangle / V_c)^{1/2}$, where n_p is the density of pins and f is the elementary pinning interaction. Previous studies have shown that, as the peak region is entered, the flux dynamics at the onset of motion changes from elastic flow to plastic flow and finally to fluid flow as H_{c2} is approached [4,5].

Measurements were carried out on two single crystal samples ($4 \times 4 \times 0.025$ and $1 \times 4 \times 0.025$ mm) of the layered low T_c superconductor $2H$-NbSe$_2$. For this material the in-plane penetration depth $\lambda_\parallel(0) \sim 2000$ Å [11] and the coherence length $\xi_\parallel(0) \sim 100$ Å. The samples were of low purity, as indicated by the depressed values of $T_c = 5.85$ and 6.15 K ($T_c \sim 7.1$ K in pure $2H$-NbSe$_2$) and low residual resistivity ratio ~ 9. Transition widths of 80 and 50 mK indicate good homogeneity. Resistance measurements employed the standard four probe technique with low resistance contacts made with Ag$_{0.1}$In$_{0.9}$ solder. The current was in the a-b plane and H along the c axis.

Figure 1 shows typical I-V curves below the peak region exhibiting pronounced history dependence. If the sample is field cooled (FC) through T_c with no applied current, we find a relatively large critical current marked I^*. But this large value is obtained only on the initial ramp up of the current. Once the flux lines are depinned, a much lower threshold current I_c is found as seen on the second ramp up. Ramping the current down from above I^* always gives the low threshold. If, however,
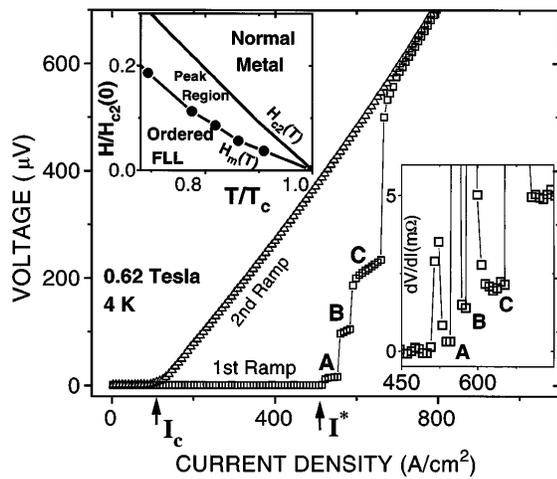
FIG. 1. I-V curves for the first and second upward ramps of the applied current after field cooling. Upper inset: the equilibrium phase diagram showing the peak effect region. Lower inset: the differential resistance dV/dI in the jumpy region near I^*. Note the three regions labeled A, B, and C, which correspond to the linear segments on the first I-V curve.
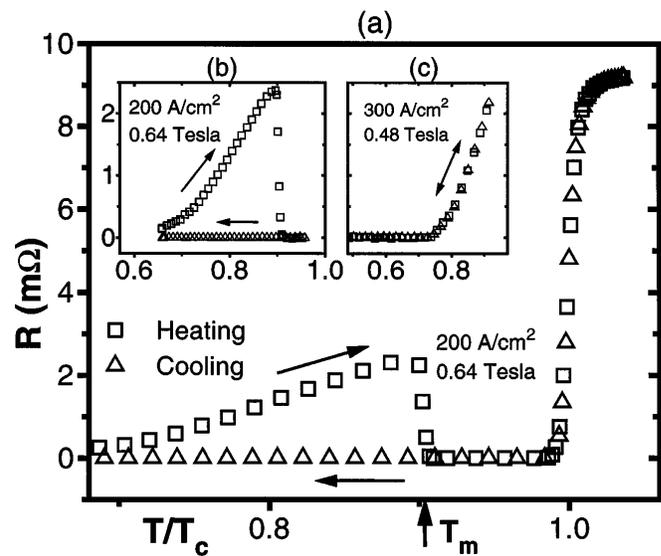

FIG. 2. Sample resistance for different temperature cyclings. In all cases the lattice was depinned with a large current before the measurement began. A much smaller current was applied as T was cycled. (a) Cycling T up through T_c and then down. (b) Cycling T up halfway into the peak region and then down. (c) Cycling T down and up without entering the peak region.

the sample is zero field cooled (ZFC), the critical current is low even on the initial ramp up (it is actually slightly lower in this case than in subsequent ramps). The ratio of I^* to I_c can be as large as 6, but approaches 1 within the peak region (Fig. 3 below). At a current above I^*, all the I-V curves join where the slope (dV/dI) agrees with the Bardeen-Stephen [12] value of $\rho_n H/H_{c2}$, indicating nearly free flux flow. At even higher currents than shown, deviation in dV/dI occurs due to sample heating. Heating effects can be large within the peak region, but they are readily identifiable and are not significant in any of the data presented here.

For a given H and T, the two thresholds, I_c and I^*, identify two distinct states of the FLL, one more strongly pinned than the other. The system may be in one or the other of these states, depending on how the lattice is formed and on its subsequent motion. For example, FC below the peak region creates a metastable strongly pinned state. The system may then be driven into the weakly pinned state by applying a large current, by changing H, or by giving the system a mechanical shock. However, changing T does not drive the system into the equilibrium state, except very near T_c.

The peak effect is seen clearly in Fig. 2 by varying T at constant H and fixed current I ($I_c < I < I^*$) as a sudden drop in resistance at a well defined T, marked by an arrow. The locus of the resistance jump defines a transition line, $H_m(T)$ (Fig. 1, upper inset), which separates the region where the weakly pinned state is stable (below the line) from the peak region (above the line) where the strongly pinned state is stable. The connection between the history dependence and the peak effect becomes clearer by cycling the system halfway into

the peak region as shown in Fig. 2(b). Here the system is prepared in the weakly pinned state by FC below the peak region and then briefly applying a current $I > I^*$. T is then raised while driving a much lower current through the sample. Upon entering the peak region the voltage drop vanishes, indicating that flux motion has stopped, and, when the sample is cooled again, the FLL remains in the strongly pinned state. This irreversibility is observed even if T is raised into the peak region only slightly. But if too large a current is used, the behavior is reversible. *The crucial factor is that the flux motion must stop in the peak region.* The same kind of T cycling measurement can be performed without entering the peak region, as shown in Fig. 2(c). The flux motion is stopped by lowering the temperature, but now the response varies smoothly and is completely reversible.

If the temperature is cycled into the peak region and back with no current flowing, no enhancement of the critical current is found unless the temperature is cycled very near to T_c. This implies that the lattice does not enter the strongly pinned configuration while in the peak region unless it is driven by a current or by thermal fluctuations. Thus the weakly pinned state is metastable in the peak region except within a narrow fluctuation region just below the transition. This metastability is difficult to observe in critical current measurements, since, if a current exceeding the low threshold is applied to this state, the FLL starts moving, but it quickly finds a more strongly pinned state and stops. However, we show below that this transient motion can be observed directly in pulse response measurements.

We now examine the field dependence of I_c and I^* in Fig. 3. The I_c curve was obtained by an initial ZFC followed by I-V measurements for a sequence of fields. Obtaining the I^* curve is more difficult, since varying H drives the system out of the metastable state, so each point represents the threshold current in the first ramp up after FC through T_c. We note that in the weakly pinned state, I_c has a $1/H$ dependence below the peak region. In the LO model this behavior reflects the increase in FLL rigidity with increasing field and is typical of a weakly disordered lattice. In the FC case, there is a wide range of fields below the peak over which I^* depends relatively weakly on field. This indicates that correlations do not play an important role and that the FLL must be highly disordered. At a field marked H_m, I_c shows an abrupt jump up to a value close to the I^* curve. At a slightly higher field the two curves merge completely. A similar jump can be seen in the T dependence (Fig. 3, inset).

These results point to the origins of the disordered state and of the metastability. The jump in I_c at H_m reflects a sharp decrease in V_c which accompanies a sudden drop or vanishing of an elastic modulus. Thus, as the FLL enters the peak region it undergoes a transition to another, less ordered phase [13]. Field cooling the disordered phase, without sufficient current to allow the flux motion to explore the phase space, freezes in the disordered structure into a metastable, "supercooled" state, leading to the large values of I^*. Upon driving this metastable state sufficiently hard, the system anneals into the equilibrium ordered state which has a large V_c and thus a much smaller value of I_{crit}. In the opposite case when $H_m(T)$ is crossed from the ordered state with pinned flux lines, a metastable ("superheated") ordered structure is formed that anneals into a disordered equilibrium state when external forces make the flux lines mobile enough to find this state.
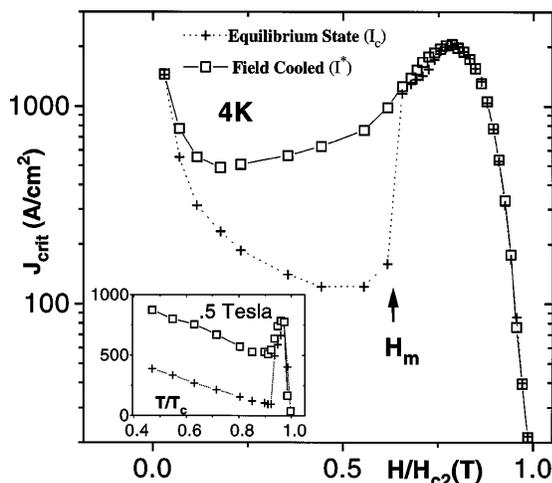
We also note that $I_c(H)$ and $I^*(H)$ join at very low fields (Fig. 3). This is due to the fact that at low fields the FLL becomes dilute, decreasing the relevance of correlations and enhancing the effect of disorder. What relation, if any, the merger bears to a reentrant liquid phase [14] remains unclear.

We now demonstrate that the pulsed current technique described below provides direct access to the annealing kinetics. The sample is first prepared in the disordered state by FC with zero applied current. Then a current pulse $I > I^*$ is applied while the voltage drop is monitored. Figure 4(a) shows the response to two successive pulses: The first exhibits a long response time t_r as the disordered state depins and forms a more ordered lattice [15]. In the second pulse the response is that of the ordered lattice and is instantaneous. The response time of the disordered state exhibits a remarkably strong current dependence: t_r changes by nearly 5 orders of magnitude upon changing the pulse height by only a factor of 3. The data for all measured H and T fit a $t_r \propto [(I - I^*)/I^*]^{-\alpha}$, with $\alpha \sim 4$ increasing slightly with field, as shown in Fig. 4(c). The data also fit a $t_r \propto \exp\{[I^*/(I - I^*)]^{1/2}\}$ fairly well. The divergence of the time scale suggests the existence of an underlying dynamical transition at I^*.

We also used this method to observe the complementary situation: the metastability of the ordered state in the
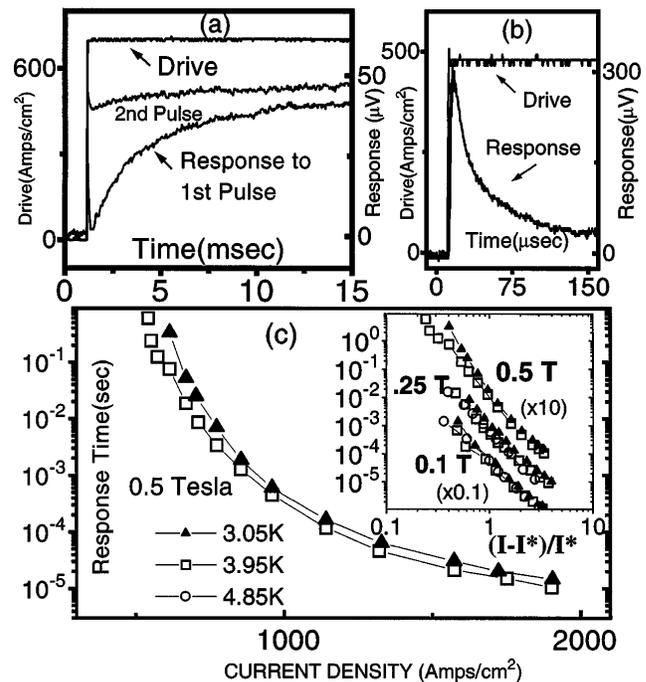
FIG. 4. Response of the FLL to pulsed currents. (a) Two consecutive pulses after field cooling through T_c to a point below peak region. (The narrow voltage spike is due to pickup.) (b) After warming the weakly pinned state into the peak region. (c) Current dependence of the response time of the strongly pinned state. Inset: t_r vs $(I - I^*)/I^*$ for several fields and temperatures. The data for 0.1 and 0.5 T were shifted for clarity by the numerical factors shown.

FIG. 3. Field dependence of the critical current density J_{crit} at 4.2 K. Inset: temperature dependence of J_{crit} at 0.5 T.

peak region. The system is prepared in the ordered state and heated into the peak region with zero applied current. Subsequently, the current is pulsed with an amplitude I ($I_c < I < I^*$). We find an initial response which is instantaneous, as in the ordered phase, but drops quickly and dramatically, as the moving lattice finds a more strongly pinned configuration [Fig. 4(b)]. This indicates that both superheating and supercooling occur across the equilibrium phase boundary at $H_m(T)$.

The results presented here provide a new basis for understanding the depinning of disordered flux lattices. A commonly used model of depinning is as a process of driving the FLL over a static barrier whose height is taken to be the dc critical driving force. However, the net force on a FLL gives its instantaneous center of mass velocity, and, thus, according to the model, if the system is driven with a current $I > I^*$, the FLL should respond instantaneously. The existence of long response times shows that the pinning force can momentarily be much larger than the value implied by the size of I^* and that the depinning transition is more complicated. This is not surprising since the model neglects the internal degrees of freedom of the lattice, which are important here. A more accurate description of depinning for the disordered lattice is as a dynamical transition with long relaxation times associated with reordering.

The data in the "jumpy" transition region just above I^* (Fig. 1) in the I-V curve for the disordered state indicate that the onset of motion is in the form of channels of flowing flux lines [3,4]. In this scenario, the jumps are the result of the sudden depinning of some fraction of the flux lines, while the linear segments between jumps reflect the increasing speed of the moving flux lines as the current is raised. Estimates of the moving fraction f can be made by comparing the voltage and differential resistance R_d (Fig. 1, lower inset) in the linear segments to their values in the equilibrium state. For the three segments shown in Fig. 1, we obtain $f = 0.04, 0.22, 0.43$, and $f = 0.06, 0.30, 0.39$ from the values of V and R_d, respectively.

The existence of motion in channels may provide insight into the long response times. One possibility is that when a current $I > I^*$ is applied, a few flux lines start moving along continuous channels which open across the sample, with the number of open channels depending on I. The moving segments of the FLL order and expand outwards until they engulf the entire sample, at which point the system is indistinguishable from the moving weakly pinned phase. This growth process could lead to the long relaxation times. The apparent divergence of t_r at I^* may reflect a divergence in the length scale of the separation between adjacent channels.

In conclusion, we have observed that the FLL can be prepared in metastable states which are sufficiently robust to allow detailed study of their transport properties. Annealing of the metastable states reveals glassy relaxation times which are strongly dependent on the driving current. While these results were obtained in $2H$-NbSe$_2$, they appear to reflect only the properties of the FLL and the disorder, and therefore should be valid in other superconductors with comparable levels of disorder. We hope these results will stimulate experimental and theoretical work on the annealing mechanism and how it is affected by disorder.

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