Depinning of a Metastable Disordered Vortex Lattice

Z. L. Xiao and E. Y. Andrei
Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08855

P. Shuk and M. Greenblatt
Department of Chemistry, Rutgers University, Piscataway, New Jersey 08855
(Received 5 July 2000)

We report on experiments investigating the depinning dynamics of a strongly pinned vortex lattice in $2H$-$NbSe_2$. We find that the depinning process starts at currents that are well below the critical current of the entire lattice and that it is governed by the formation of contiguous channels of mobile vortices connecting the sample edges. We obtain the formation time of the first channel by monitoring the delayed voltage response to a driving current step and by measuring the ramping rate dependence of the critical current. The subsequent increase in the number of moving vortices is determined from the temporal evolution of the voltage response and the critical current.

DOI: 10.1103/PhysRevLett.86.2431 PACS numbers: 74.60.Ge, 74.60.Ec, 74.60.Jg

Pinning of vortices in type II superconductors is crucial for dissipationless transport. As long as the applied current is sufficiently low, the vortices are immobile and the superconducting properties are maintained. But as the current is increased beyond a critical value the vortices become unpinned and dissipation sets in. The depinning process is an intricate phenomenon of collective transport in a random medium which is a sensitive function of the vortex state and the properties of the pinning potential. Recent theory and simulations [1–4] indicate that a weakly pinned vortex lattice will unpin elastically without breaking, while a strongly pinned one can break up in the form of isolated channels of mobile vortices. Experimentally, channels in vortex matter were observed with techniques such as Bitter decoration and scanning tunneling microscopy [5]. The mechanism of channel depinning was proposed to explain the stepwise structure observed in the current-voltage (I-V) curves of a strongly pinned vortex lattice [6]. In this Letter, we present experiments which are consistent with a mechanism of channel depinning in a disordered vortex lattice and provide a measure of the channel formation and its evolution with time.

A strongly pinned vortex lattice is prepared by field cooling (FC) the sample from above the critical temperature T_c in the presence of a magnetic field. The depinning process of the resulting disordered vortex lattice is monitored by measuring the evolution of the voltage response to a subcritical current. We find that the vortices in this state do not depin elastically but rather through the formation of regions in which the vortices are ordered and weakly pinned. The growth and proliferation of these regions leads to the creation of channels of mobile vortices. These weakly pinned channels can form at current amplitudes that are well below the critical current of the entire lattice and do not form instantaneously but evolve gradually over time scales that can be resolved in our experiments. The channel formation time, which decreases rapidly with increasing current, manifests itself via a delayed voltage response to a driving current. This leads to a ramping rate dependence of the I-V curves and of the measured critical currents. The lowest critical current, obtained for slow ramping rates, is found to be equal to the critical current of the ordered state obtained by zero field cooling (ZFC). In order to observe the higher critical current of the pristine FC state, the measurement has to be sufficiently fast to preempt the formation of ordered regions. It follows that, in the standard slow transport experiments, a metastable state of a disordered vortex lattice such as the pristine FC state can easily be missed.

The pure single crystal of $2H$-$NbSe_2$ on which the data were acquired has a size of $3(l) \times 0.65(w) \times 0.025(d)$ mm^3 and a T_c of 7.1 K with a transition width of 80 mK in zero magnetic field. Our measurements employed a four probe technique with low resistance contacts made of $Ag_{0.1}In_{0.9}$ solder, and the distance between the two voltage contacts is 1.5 mm. The experiments monitor the I-V 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 ($4nV/\mathrm{Hz}^{1/2}$) and recorded with a 100 MHz digital oscilloscope. In order to reduce noise, the fast transport data were averaged over ten runs (initiating the system with a field cooling cycle from above T_c for each run). For the slower current ramps, we used a digital to analog converter board and/or a commercial current source (Keithley 2400), and the corresponding voltage response was read with a commercial nanovoltmeter (Keithley 181). The magnetic field was kept along the c axis of the sample and the current was applied in the ab plane. The ZFC and FC vortex lattices are prepared by applying the magnetic field after and before cooling the sample through T_c, respectively. No current was applied during the cooling process. The critical current, I_c, is defined as the current at which the voltage response reaches 5 μV.

Previous results in both low- and high-T_c superconductors [6–14] show that the FC states of the vortex lattice are metastable and disordered, whereas the ZFC state is stable and ordered. The metastable FC state can be driven to the stable ordered state by applying a dc current [6–10] or by varying the magnetic field [11–13]. While the metastable state of the FC lattice in pure $2H$-$NbSe_2$, NbTa, and $Bi_2Sr_2CaCu_2O_{8+\delta}$ can be detected with small angle neutron scattering or fast transport measurements, it is absent in the usual slow transport or magnetization measurements [8–12]. The speed of the measurements is thus an important parameter in these experiments. This is illustrated in Fig. 1, where we plot the ramping rate dependence of the I-V curves for a FC vortex lattice, at $T = 4.441$ K and $B = 1$ T. We note that the current at which a detectable voltage appears shifts to higher values with increasing ramping rate. As the current is increased, the ramping rate dependence becomes less pronounced and eventually disappears completely. By contrast, we find that there is no ramping rate dependence in the I-V curves of the ZFC vortex lattice measured at the same temperature and field. We thus conclude that the observed ramping rate dependence in the FC case must be intrinsic and not an instrumental artifact. This becomes evident by comparing the I-V curves measured with the first and second ramps after field cooling, where the I-V curve obtained on the second ramp has a much lower I_c.

The ramping rate dependence of the critical current, $I_c(S)$, obtained from I-V curves measured on pristine FC states, is presented in Fig. 2. The figure inset shows the temperature dependence, $I_c(T)$, for several ramping rates for the FC and ZFC states. We note the pronounced peak effect at T_p which is readily seen in these samples with slow transport measurements [6]. At low ramping rates, the $I_c(T)$ curves of the FC and ZFC states overlap at all temperatures. As the ramping rate is increased, the $I_c(T)$ of the ZFC state remains unchanged, while that of the FC state increases for temperatures $T < T_p$ and is unchanged for $T > T_p$. This leads to a disappearance of the peak effect for the FC state at high ramping rates.

The pronounced ramping rate dependence of the I-V curves and I_c is a first indication of a finite transition time from the metastable FC lattice to the stable state. When the ramping rate is fast enough, the vortices in the FC lattice have little time to make the transition to the more ordered stable state, and the measured I_c is thus close to that of the pristine disordered lattice. But when given enough time in the presence of a current, as in the slow measurements, the FC vortex lattice becomes ordered resulting in I-V curves that are identical to those of the ZFC state. Remarkably, this process takes place even for driving currents that are significantly lower than the current needed to unpin the entire disordered lattice. This strongly suggests that the depinning process is not elastic but rather involves the formation of a region of more weakly pinned channels where the vortices start moving first. This is consistent with the theoretical models and simulations [1–4] which favor a mechanism of channel formation for the depinning of a strongly pinned lattice.

Because the nucleation and growth of the ordered phase is not instantaneous, one can expect a delayed voltage response of the vortex lattice to a current step. As we show in the inset of Fig. 3, this is indeed what is observed—the

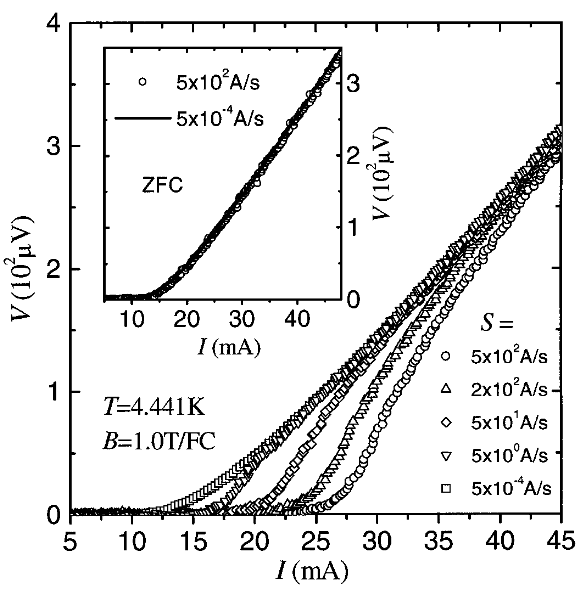

FIG. 1. I-V curves for FC lattice at various ramping rates. Inset: I-V curves at the same T and B for ZFC lattice at ramping rates of $S = 5 \times 10^{-4}$ A/s and 5×10^{2} A/s.

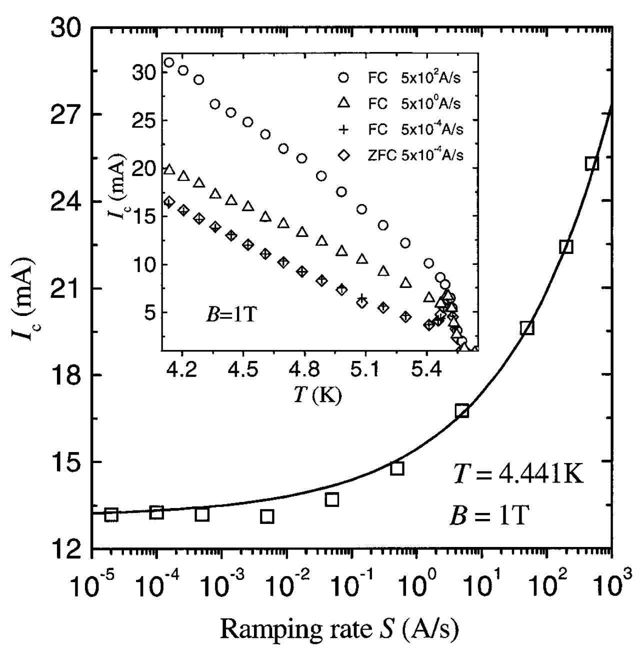

FIG. 2. Ramping rate dependence of critical current. The solid curve is a fit to $I_c(S) = I_{c0} + cS^{1/1+\alpha}$ with $I_{c0} = 13.12$ mA, $c = 2.31$, and $\alpha = 2.8$. Inset: Temperature and ramping rate dependence of critical current for FC and ZFC lattice.

voltage response lags behind the current step, appearing only after a delay time t_d. The delay time, shown in Fig. 3, is a sensitive function of temperature and current. It is shortest for the highest driving currents and increases with decreasing current and decreasing temperature. The current dependence of t_d can be fit with a simple power law $t_d \sim (I - I_{co})^{-\alpha}$, shown as a solid line, with α ranging from 2.9 at 4.441 K to 3.5 at 5.295 K.

One can obtain a simple estimate of the ramping rate dependence of I_c by assuming a channel growth rate of $v(I,T,H) = L/t_d$, where L is the length of the (first) channel. Using this model and the measured current dependence of the delay time $t_d \sim (I - I_{co})^{-\alpha}$ leads to a simple expression for the ramping rate dependence of the critical current: $I_c(S) = I_{co} + cS^{1/1+\alpha}$, where $I_c(S)$ is the current for which the first channel is completed and c is a constant. The fit of this form to the critical current obtained at $B = 1$ T and $T = 4.441$ K and various current ramping rates is shown in Fig. 2 as a solid curve. Through this fit we obtained $\alpha = 2.8$, which is close to $\alpha = 2.9$ derived from the fit of the current dependence of the delay time at the same temperature and magnetic field.

A more direct test of the channel depinning model is afforded by measuring the time dependence of I_c during the evolution of the FC lattice. This was accomplished by taking advantage of the fact that the evolution is completely arrested in the absence of current, which is often the case in strong pinning materials or low-T_c superconductors, where the pinning barriers are larger than thermal fluctuations. In such systems, the configuration of a moving lattice can be frozen by suddenly removing the driving current. Such a "memory effect" was previously observed in $YBa_2Cu_3O_x$ [15,16] near the melting transition and in the lower part of the peak in Fe-doped $2H$-$NbSe_2$ [17]. A similar effect is observed in undoped $2H$-$NbSe_2$ [9] indicating that the quenched vortex lattice retains the configuration of the moving lattice at the moment of the quench and stores it for a long time (at least 10 h). Our experiment consists of applying a current step for a time t_0 and then removing it, thereby freezing the instantaneous vortex configuration. The information is then retrieved from the instantaneous I-V of the quenched vortex lattice which is measured with a fast current ramp. The results for $T = 4.2$ K, $B = 1.8$ T, and current steps of amplitude 15 mA are plotted in Fig. 4. Within the experimental resolution, the I-V curves are all the same for very short quench times $t_0 < t_d = 4 \times 10^{-5}$ s. In the limit of long times $t_0 = 10$ s, the I-V curves coincide with those of the ZFC lattice. The evidence on channel depinning emerges at intermediate values of t_0. For example, the I-V curve at $t_0 = 3 \times 10^{-4}$ s (point C in the upper inset) shows that the vortex lattice at that moment has the same critical current as that of the ordered state, meaning that there is at least one channel across the sample in which the vortices are ordered. In fact, this is the case for all later times $t_0 > 3 \times 10^{-4}$ s (points D to I in the upper inset). The number of vortices moving in these ordered channels can be inferred from the voltage response by assuming that the moving vortices are in the free flux flow

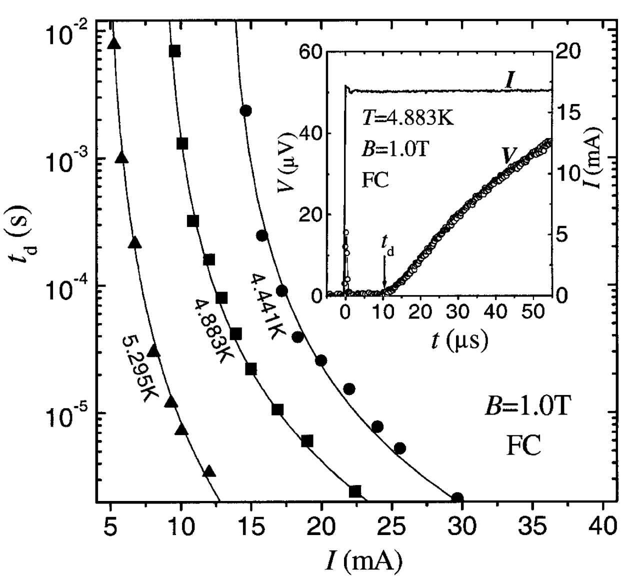

FIG. 3. Driving current dependence of the delay time t_d at various temperatures. The solid curves are fits to $t_d \sim (I - I_c)^{-\alpha}$. Inset: Definition of t_d.

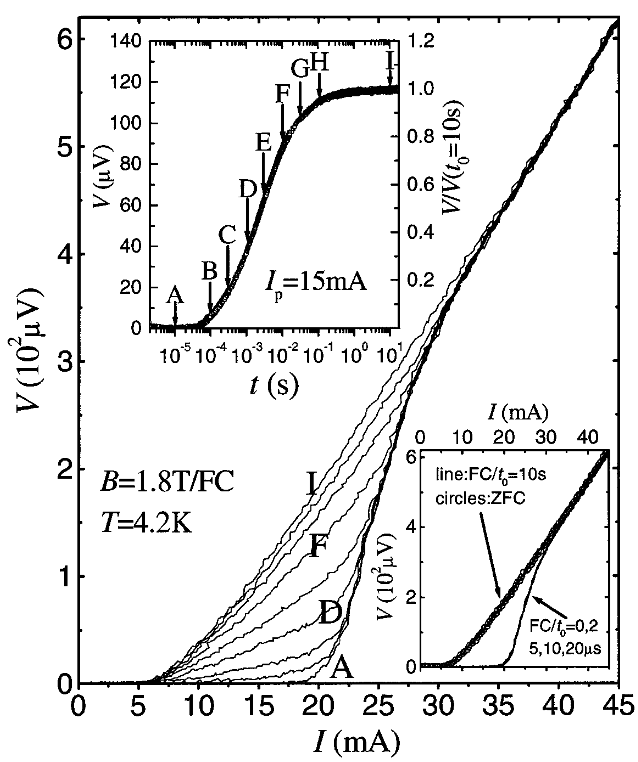

FIG. 4. I-V curves at $T = 4.2$ K and $B = 1.8$ T for $S = 200$ A/s at various times as indicated in the upper inset, where A to I correspond to $t_0 = 10^{-5}$, 10^{-4}, 3×10^{-4}, 10^{-3}, 3×10^{-3}, 10^{-2}, 3×10^{-2}, 10^{-1}, and 10 s. Lower inset: I-V curves before channel formation at $t_0 = 0$, 2, 5, 10, and 20 μs and after reordering at $t_0 = 10$ s. The I-V curve of a ZFC lattice is shown for comparison.

regime, where their velocity is determined by the Lorentz force and Bardeen-Stephen viscosity. In this case, the voltage is expressed as $V \sim n(I - I_c)$ [18], where n is the number of moving vortices, and I_c is the critical current. Thus, since we observe a voltage increase with time when both I and I_c are fixed, it must be a consequence of a growing number of mobile vortices. When the voltage saturates for $t_0 > 10$ s, the Bardeen-Stephen resistivity is recovered, indicating that all the vortices have joined the motion. These results are in agreement with those observed in computer simulation by Olson *et al.* [4] but are inconsistent with models proposing a continuous evolution of the critical current [19].

We now revisit the entire experimental data in view of our proposed model for a depinning mechanism governed by current driven vortex ordering and the formation of mobile vortex channels. In the absence of a driving current, the field cooled vortex lattice is in a metastable disordered state with critical current density J_c everywhere in the sample. When a subcritical current $I < I_c$ is applied, it initially flows along each edge within a strip taking up a fraction I/I_c of the sample width and carrying a current density J_c. Within the regions where the current penetrates, it facilitates local rearrangements of disordered vortices into the thermodynamically stable ordered state, thereby reducing the local current density to J_{co}. 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. We note that, before the formation of this path, the vortex motion is limited to local rearrangements during the disorder-to-order conversions with practically no macroscopic motion (displacements are less than a lattice spacing) which does not produce a detectable voltage signal. The measured t_d is thus the formation time of the first mobile vortex channel tranversing the sample. This time is governed by the random process of current driven rearrangements, and is related to neither the traversal time of free ordered vortices (about 30 ms at $I = 15$ mA in Fig. 4) nor the diffusion time of the pristine FC vortices (larger than 400 μs at $I = 15$ mA in Fig. 4) across the sample. As the vortices move along this path and become motionally ordered, the critical current will drop to the value in the ordered state I_{co}. This is clearly seen in Fig. 4 where, for $t_0 \sim 300$ μs, at point C, the critical current has dropped to its lowest value. From the resistivity of the corresponding I-V curve, we conclude that at this time about 17% of the vortices move in the ordered channel (or channels). At later times, the voltage increase is caused by more vortices joining the motion. This can occur by either lateral expansion of individual channels or through the formation of new channels. As the reordering and depinning processes proceed, the voltage continues to increase and saturates at $t_0 \geq 10$ s when all the vortices have ordered.

In summary, the experiments presented here provide information on the depinning process of a strongly pinned vortex lattice. We find that depinning is governed by current driven vortex rearrangements leading to the formation of regions with weakly pinned vortices. These vortex rearrangements occur without a measurable voltage response, which appears only upon the creation of a channel of mobile vortices connecting the sample edges. The creation time of such channels gives rise to the observed delays in voltage response to subcritical driving currents as well as to the ramping rate dependence of the critical currents.

We thank C. J. Olson for preprints, and W. Henderson, P. H. Kes, X. S. Ling, C. J. Olson, Y. Paltiel, C. Reichhardt, A. Rosch, and E. Zeldov for stimulating discussion. This work was supported by NSF-DMR-9705389 and by DOE DE-FG02-99ER45742.

[1] O. Narayan and D. S. Fisher, Phys. Rev. B **49**, 9469 (1994); J. Watson and D. S. Fisher, Phys. Rev. B **55**, 14 909 (1997).
[2] M. C. Faleski, M. C. Marchetti, and A. A. Middleton, Phys. Rev. B **54**, 12 427 (1996).
[3] S. Scheidl and V. M. Vinokur, Phys. Rev. B **57**, 2574 (1998).
[4] C. J. Olson, C. Reichhardt, and F. Nori, Phys. Rev. Lett. **80**, 2197 (1998); C. J. Olson *et al.,* cond-mat/0006172 (2000).
[5] M. Marcheevsky *et al.,* Phys. Rev. Lett. **78**, 531 (1997); A. M. Troyanovski, J. Aarts, and P. H. Kes, Nature (London) **399**, 665 (1999).
[6] W. Henderson *et al.,* Phys. Rev. Lett. **77**, 2077 (1996); E. Y. Andrei *et al.,* J. Phys. (Paris) IV **10**, 5 (1999); M. Danckwerts *et al.,* Phys. Rev. B **59**, R6624 (1999).
[7] C. Baker and J. Sutton, Philos. Mag. **19**, 1223 (1969); J. A. Good and E. J. Kramer, *ibid.* **24**, 339 (1971).
[8] U. Yaron *et al.,* Phys. Rev. Lett. **73**, 2748 (1994); Nature (London) **376**, 753 (1995).
[9] Z. L. Xiao, E. Y. Andrei, P. Shuk, and M. Greenblatt, Phys. Rev. Lett. **85**, 3265 (2000).
[10] S. L. Lee *et al.,* Physica (Amsterdam) **276B–278B**, 752 (2000).
[11] S. S. Banerjee *et al.,* Appl. Phys. Lett. **74**, 126 (1999); Phys. Rev. B **59**, 6043 (1999).
[12] B. Sas *et al.,* Phys. Rev. B **61**, 9118 (2000).
[13] I. Joumard *et al.,* Physica (Amsterdam) **341C–348C**, 1067 (2000); C. Goupil *et al.,* Physica (Amsterdam) **341C–348C**, 999 (2000).
[14] X. S. Ling *et al.,* Phys. Rev. Lett. **86**, 712 (2001).
[15] S. N. Gordeev *et al.,* Nature (London) **385**, 324 (1997).
[16] S. O. Valenzuela and V. Bekeris, Phys. Rev. Lett. **84**, 4000 (2000).
[17] Z. L. Xiao, E. Y. Andrei, and M. J. Higgins, Phys. Rev. Lett. **83**, 1664 (1999).
[18] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. **139**, A1163 (1965).
[19] Y. Paltiel *et al.,* Nature (London) **403**, 398 (2000); G. Ravikumar, cond-mat/0009254 (2000).