# Equilibration and Dynamic Phase Transitions of a Driven Vortex Lattice

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We report on the observation of two types of current driven transitions in metastable vortex lattices. The metastable states, which are missed in usual slow transport measurements, are detected with a fast transport technique in the vortex lattice of undoped $2H$-$NbSe_2$. The transitions are seen by following the evolution of these states when driven by a current. At low currents we observe an equilibration transition from a metastable to a stable state, followed by a dynamic crystallization transition at high currents.

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Vortices in type II superconductors are easily trapped in long-lived metastable states created by the random pinning potential [1]. A driving current assists in vortex detrapping and in finding the stable states [2–5], in essence assuming the role of temperature in ordinary phase transitions. This analogy was pointed out by Koshelev and Vinokur (KV) who showed that when the vortices are set in motion by a current $I$, the random potential appears as a temporally fluctuating Langevin force in the moving frame [6]. The random potential can then be replaced by a "shaking temperature" $T_s \propto 1/I$, which leads to a simpler problem of a pure system at an effective temperature $T_{\mathrm{eff}} = T + T_s$. Thus, if the pure system crystallizes at a temperature $T_m$, the actual system will crystallize when driven by a current $I_t \propto (T_m - T)^{-1}$. This KV transition separates a disordered state at low currents from an ordered one at high currents. Further work [7–12] predicted that the transition is preceded by a regime of plastic flow followed by smectic ordering. Small angle neutron scattering (SANS) on the field-cooled (FC) vortex lattice in undoped $2H$-$NbSe_2$ [13] provided evidence for current induced ordering. These data are generally accepted as direct evidence for the KV transition [9,11,14] despite the fact that for usual slow transport measurements under the same experimental conditions the transition is absent [13,15,16]. This discrepancy could be an indication of metastability in the FC vortex state, in which case the observed ordering in the SANS data would be an "equilibration"—from a metastable disordered state to a stable ordered one—rather than the KV transition. Thus far, however, metastability in the vortex lattice of undoped $2H$-$NbSe_2$ was thought to be absent [13].

In this Letter we present results of fast transport measurements that demonstrate the existence of metastable states in undoped $2H$-$NbSe_2$. The experiments probe the dynamic transitions with emphasis on distinguishing between equilibration and the KV transition. We show that the current induced transition in the FC state is in fact an equilibration from a disordered metastable state to an ordered stable state and not the KV transition. We further find that in the peak effect region (a region of the phase diagram, just below $H_{c2}$ where the critical current increases with field and temperature [3]) the vortex lattice can undergo two current induced transitions. The first is an equilibration transition observed at low currents which is then followed by the KV crystallization at much higher currents.

The sample was an undoped single crystal $2H$-$NbSe_2$ platelet of dimensions $1.5 \times 0.65 \times 0.025$ mm$^3$. Its critical temperature $T_c$ was 7.1 K, the transition width 80 mK, and the normal resistance near $T_c$ was $21 \times 10^{-3}$ Ω. A four probe measurement with low resistance AgIn solder contacts was used to monitor vortex response. The response to fast current ramps (FCR)—200 A/s—was detected with a fast (2 $\mu$s response time) amplifier while the slow current ramp (SCR)—$5 \times 10^{-5}$ A/s—measurements were obtained with a Keithley 181 nanovoltmeter. The magnetic field was kept along the $c$ axis of the sample and the current was in the $a$-$b$ plane. The zero-field-cooled (ZFC) and the FC vortex lattices were prepared by applying the magnetic field after or before cooling the sample through $T_c$, respectively, in the absence of applied current. The degree of order of the vortex lattice was inferred from the critical current, $I_c$ (defined by a 5 $\mu$V response criterion), by using the Larkin-Ovchinnikov model [17], according to which $I_c$ grows with the degree of disorder.

In Fig. 1 we compare the current-voltage ($I$-$V$) curves of the FC and ZFC lattices. When probed with slow current ramps the response of the two states is identical and no evidence of metastability is observed. This is in contrast to results in Fe doped $2H$-$NbSe_2$ where strong metastability and hysteresis were found in slow transport measurements [4]. Here the temperature dependence of the critical currents [inset in Fig. 1(a)] is the same for both states and exhibits a pronounced peak effect just below $T_c$. But in spite of the identical response in slow measurements, the initial vortex states prepared by ZFC and by FC are not identical.

The difference between the two states becomes evident only in fast measurements. This is illustrated in Fig. 1(b) where significant hysteresis is seen when comparing the

  

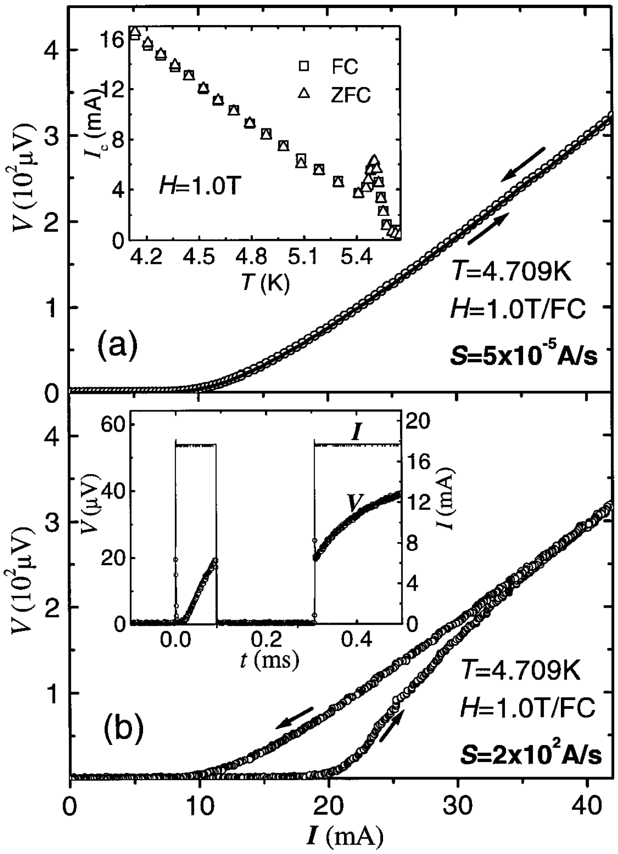


FIG. 1. (a) $I$-$V$ curves obtained with slow ($5 \times 10^{-5}$ A/s) current ramps. The inset shows the temperature dependence of the critical current for ZFC and FC vortex lattices obtained with slow measurements. (b) Fast $I$-$V$ curves (200 A/s) for an FC vortex lattice. The inset shows the time evolution of the response of an FC vortex lattice to a current step.

fast $I$-$V$ curve for the pristine FC state, measured on the first ramp-up of the current, with that recorded when the current is ramped down. The critical current of the pristine FC state is almost twice that of the annealed state recorded on the down ramp, indicating that it is more disordered. By contrast the pristine ZFC state starts out with a low critical current, is unchanged by current cycling, and its $I$-$V$ curves are independent of ramping speeds. We conclude that the ZFC state is ordered and stable. For the FC state, the $I$-$V$ curves obtained after the first ramp-up (including the ramp down and all subsequent ramps) are identical to those of the ZFC state indicating that the FC lattice reorders during the first ramp. It follows that the FC lattice is initially in a disordered metastable state which reorganizes under the influence of a current into a stable ordered configuration.

The current driven organization of the FC lattice is seen directly in the inset in Fig. 1(b) through the evolution of the response to a current step. After an initial waiting time the response starts growing from zero as the vortices order into a state with lower critical current, and saturates to a value that depends on the amplitude of the applied current. In order to study the current dependence of the reorganization the pristine FC state was driven with long (100 s) current steps and then quenched by suddenly removing the current. When the current is removed the evolution of the vortex state is arrested instantaneously (within the experimental resolution) and then resumes from the exact same state when the current is turned back on. This is clearly seen in the inset in Fig. 1(b). Thus, when the quenched state is probed by recording the $I$-$V$ curve with a fast current ramp the critical current reflects the degree of order of the state at the moment of quenching.

In Fig. 2(a) we plot the critical current of the quenched state as a function of current-step amplitude. No evolution is seen until $I^* = 6.7$ mA where we note the onset of a sharp transition from a disordered state (higher $I_c$) to an ordered state (lower $I_c$). The transition is completed at $I_{cs} = 8$ mA, at which point the voltage response becomes measurable in the $I$-$V$ curve. Also shown are the results for the same experiment on the pristine ZFC lattice and the annealed FC and ZFC lattices. The vortex lattice was annealed with a slow ($5 \times 10^{-5}$ A/s) cycle of the current between 0 and 50 mA. The absence of a jump in $I_c$ indicates that the current does not cause ordering of the ZFC and annealed states. For higher amplitude current

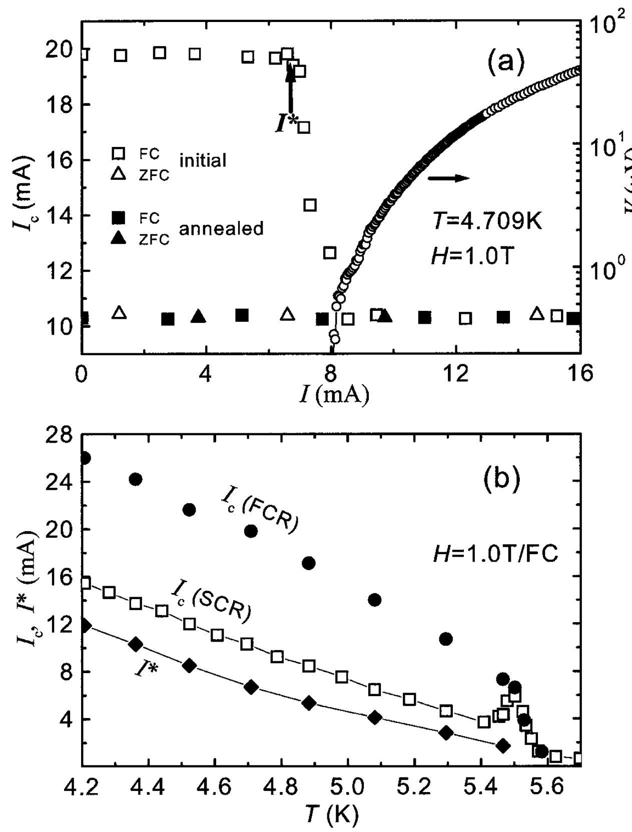


FIG. 2. (a) Critical currents for initial and annealed vortex lattices prepared by ZFC and FC processes following a 100 s drive with various currents, $I$. The open circles are the $I$-$V$ curve of an FC vortex lattice obtained in a slow measurement. (b) Temperature dependence of $I^*$ and the critical currents of the FC lattice for fast (FCR) and slow (SCR) measurements.

steps, $I > I_{cs}$, the $I$-$V$ curves of all quenched states are identical, regardless of the initial state. The transition at $I^*$ is the same as that seen in the SANS measurements and interpreted as the KV crystallization [13]. But the fact that it occurs at such low currents makes it an unlikely candidate for the KV transition. This is confirmed by the temperature dependence of $I^*$, shown in Fig. 2(b). Here $I^*$ decreases with increasing temperature, in contrast to the predicted increase with temperature for the KV transition. We conclude that $I^*$ is not where the KV transition occurs but rather the onset of a current driven equilibration from the metastable disordered FC state to a stable ordered state.

To illustrate further the difference between the equilibration and the KV transition we repeated the above experiment in the peak effect region, where the KV transition [15,18] and a current driven reorganization in the ZFC lattice [5] were seen with transport measurements. Since much higher currents are required in order to observe the KV transition, Joule heating needs to be considered. For example, for a 45 mA continuous current drive (the highest current in Fig. 3), a temperature increase of 25 mK in the sample was detected. The details on the determination of Joule heating in these experiments are presented elsewhere [19]. To avoid heating at high currents we apply the current in a sequence of short, 10 $\mu$s pulses separated by 500 $\mu$s cooling intervals with no current. For currents below 15 mA pulsing was not necessary since heating was negligible (less than 3 mK) and the measured $I_c$ was the same for continuous and pulsed applications. In the following discussion we focus on the data which show no heating. In Fig. 3(a) we show the critical current of the quenched vortex lattice following the application of 100 s current steps of various amplitudes. At low currents $I \leq I^* = 4.5$ mA no measurable change occurs in the vortex states. For higher currents, $I^* < I < I_{cs} = 8.6$ mA the current driven organization sets in, affecting each state differently. The critical current of the FC state drops rapidly, that of the ZFC state increases, while the annealed lattice curve is almost unchanged. At $I_{cs}$ all the curves converge, overlapping at higher currents, which indicates that in this regime the vortex state is determined by the driving current alone and is independent of the initial preparation. The critical current decreases with increasing current step amplitude saturating at a value which is lower than that of the stationary vortex lattices, as expected for the KV transition.

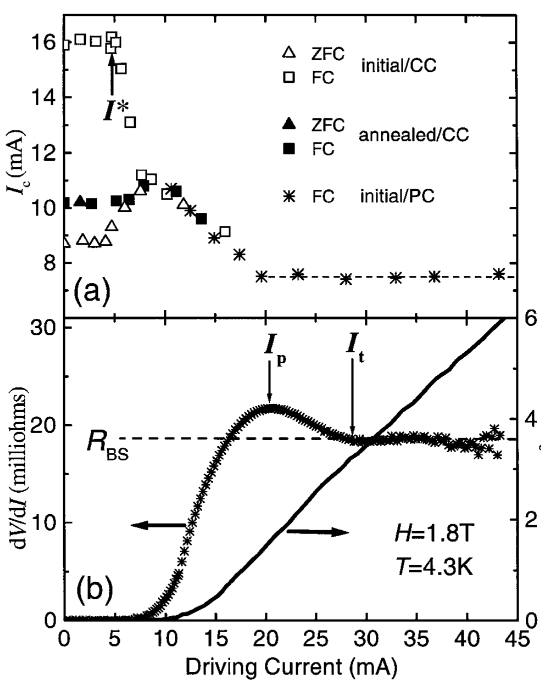


FIG. 3. (a) Evolution of the critical current with driving current amplitude for ZFC, FC, and annealed vortex lattices in the peak effect region following a 100 s drive with continuous (CC) and pulsed (PC) currents. (b) Current dependence of differential resistance illustrating the definition of $I_p$ and $I_t$. $R_{BS}$ is the Bardeen-Stephen free flux flow value. Also shown is the $I$-$V$ curve obtained with a pulsed current.

In order to identify the KV crystallization we follow the usual approach in transport measurements focusing on the shape of the differential resistance curve. The differential resistance, shown in Fig. 3(b), was obtained from the $I$-$V$ curve by numerical differentiation of a polynomial fit to the data. We note that the differential resistance is vanishingly small for low currents and becomes finite only above $I_{cs}$ where metastability has disappeared. As the current is increased further the curve rises to a maximum value of 21.7 m$\Omega$ at $I_p = 20.4$ mA and then drops down saturating at the Bardeen-Stephen free flux flow value $R_{BS} = 18$ m$\Omega = R_n \mathrm{H}/\mathrm{H}_{c2}$ at $I_t = 28.8$ mA. Its shape can be interpreted according to numerical simulations on the motional organization of a vortex lattice [6,7,10,12]: at low velocities the motion is plastic leading to a defective lattice. The defect density increases with velocity resulting in a corresponding increase in differential resistance which peaks at $I_p$. At this point the vortices move in an array of almost periodic channels forming a smectic state characterized by transverse order alone. As the velocity is further increased the vortices order inside the channels eventually crystallizing at $I_t$. The temperature dependence of $I_t$, shown in Fig. 4, is consistent with the KV prediction for the crystallization with $T_m = 4.37 \pm 0.01$ K. The fact that $T_m$ essentially coincides with the peak in critical current indicates that the peak effect is associated with an underlying order-disorder transition. In the same figure we also show the curves for $I^*$, $I_c$ (SCR), $I_p$, and $I_t$ which separate the different dynamic regimes of the moving vortex system as described in the caption.

In both sets of measurements presented here the FC state is initially metastable and can reorganize into a stable state when driven by a current. The reorganization sets in at a current $I^*$ which is significantly lower than the critical current of the pristine FC state. Below the peak region, the FC state undergoes an equilibration transition at $I^*$ which leads to an ordered stable state indistinguishable from the

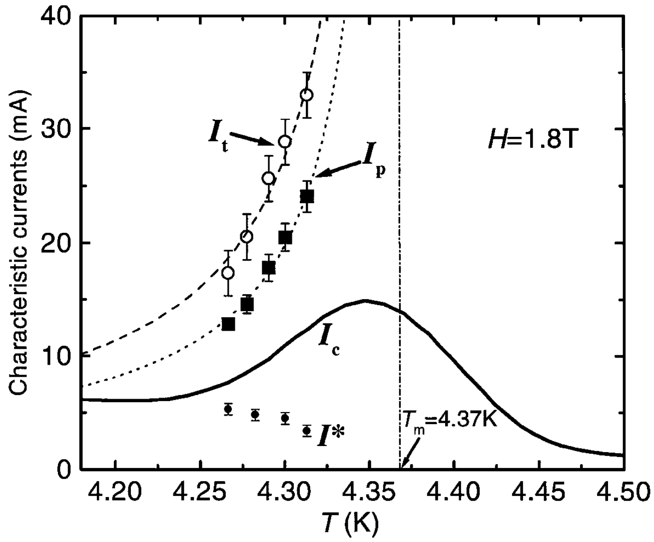


FIG. 4. Temperature dependence of the currents separating the different dynamic regimes: $I < I^*$, pinned; $I^* < I < I_c$, equilibration; $I_c < I < I_p$, plastic flow; $I_p < I < I_t$, smectic ordering; $I > I_t$, crystallization. The dashed and dotted curves show fits to the KV model.

ZFC state. By contrast the ZFC state is unaffected by the current. For the data in the peak effect region, vortex reorganization sets in at $I^*$ for *both* the FC and ZFC states. The former becomes more ordered while the latter becomes more disordered until, at $I_{cs}$, they merge into a single state and lose the distinction of their initial preparation. Thus, by analogy with the equilibration transition seen below the peak region, we conclude that in this part of the phase diagram the initial FC and ZFC states are both metastable and $I^*$ is the onset of a current driven equilibration transition to a mixed stable state.

Several aspects of these data can be understood in the context of recent Hall probe measurements on Fe doped samples [20] which have shown that in the peak effect region a stable disordered phase can be injected through a surface barrier at the sample edges. This mechanism can readily account for the disordering of the ZFC vortex lattice as indicated in Fig. 3 and in Ref. [5]. In fact, it is possible that $I^*$ is associated with a surface barrier [21], so that bulk vortices are not subject to a Lorentz force until $I^*$ is exceeded. Other features of the data can be described in terms of the phenomenological parameter for the distance that the disordered phase penetrates into the sample, $L_r(T, H, I)$. For example, $L_r \simeq 0$ below the peak where the ordered state is stable, but it is finite at low velocities in the peak region where the two phases coexist. At high velocities, where the random potential is averaged out in the moving vortex frame, $L_r \simeq 0$, which leads to a stable ordered state.

In summary, the experiments described here demonstrate that a metastable vortex lattice can undergo two types of current driven transitions. Below the peak effect region we observed a current driven equilibration transition from a metastable disordered state to a stable ordered one. In the peak effect region we detected both the equilibration and the KV transitions.

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