# 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 both field-cooled and zero-field-cooled vortex lattices in pure 2H-NbSe$_2$. The transitions are seen by following the evolution of these states when driven by a current. At low velocities we observe an equilibration transition from a metastable to a stable state, followed by a dynamic crystallization transition at high velocities.

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The question of how a system explores its phase space in the absence of thermal fluctuations arises whenever slow dynamics leads to trapping in metastable states. Well known examples are granular materials, glasses and magnetic vortices in type II superconductors [1]. Here we present experiments that show that in the latter case a driving current plays the key role in phase space exploration.

Vortices are easily trapped in long lived metastable states created by the random pinning potential. A driving current lowers the potential, assists in vortex detrapping and in finding the stable states [2–5]. In essence it assumes the role of thermal fluctuations in ordinary phase transitions. The analogy between thermal fluctuations and driving current was pointed out by Koshelev and Vinokur [6] who argued that the random potential that leads to a disordered state in the stationary vortex array appears as a temporally fluctuating Langevin force when, due to the applied current $I$, the vortices are moving with a finite velocity $v \propto I$. As a result the random potential can be replaced by a "shaking temperature" $T_s \propto 1/I$ leading to a simpler problem of a pure system at an effective temperature $T_{eff} = T + T_s$. Thus, if the melting temperature of the pure system is $T_m$, a moving vortex lattice at temperature $T < T_m$ will crystallize at a current $I_t \propto (T_m - T)^{-1}$. This Koshelev-Vinokur (KV) transition separates a disordered state at low currents from an ordered lattice at higher currents. Subsequent theoretical work [7–12] showed that the crystallization is preceded by a regime of plastic flow followed by smectic ordering. Recent imaging experiments and small angle neutron scattering (SANS), which found that a disordered vortex lattice becomes ordered in the presence of low driving currents [13–16], were interpreted as evidence for the KV transition [13].

The experiments described here use fast transport measurements to follow the evolution of driven vortex states. By capturing the process of vortex organization and its dynamics we show for the first time that under the influence of a driving current a metastable vortex state undergoes two types of dynamic transitions: an equilibration transition, observed at very low currents, which drives the system from metastable to stable state and can lead to either a more ordered or a more disordered state, depending on the initial state. This transition, which is missed in the usual slow measurements, is followed by a dynamic crystallization observed at much higher currents.

The sample was an undoped single crystal 2H-NbSe$_2$ platelet of dimensions 1.5x0.65x0.025mm$^3$. Its critical temperature $T_c$ was $7.1K$, the transition width $80mK$ and $R_c$, the normal resistance near $T_c$ was 21x10$^{-3}\Omega$. A four probe measurement with low resistance AgIn solder contacts was used to monitor vortex response. The response to fast current ramps - 200A/s- was detected with a fast ($2\mu s$ response time) amplifier while the slow ramp -$5 \times 10^{-5} A/s$- measurements were obtained with a Keithley 181 nanovoltmeter. The slow ramp differential resistance measurements employed a low frequency lock-in technique. 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 field cooled (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] which connects the size of a correlated domain $R_c$ with the critical current density $J_c \propto J_0(R_c/\xi)^2$. Here $J_0$ is the depairing current density and $\xi$ the coherence length.

In Fig.1 we compare the current-voltage ($I-V$) curves of the FC and ZFC lattices. When probed with slow current ramps, shown in Fig. 1(a), the response of the two states is identical and no hysteresis is observed, in accord with previous reports [3,13]. The temperature dependence of the critical currents (inset of 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

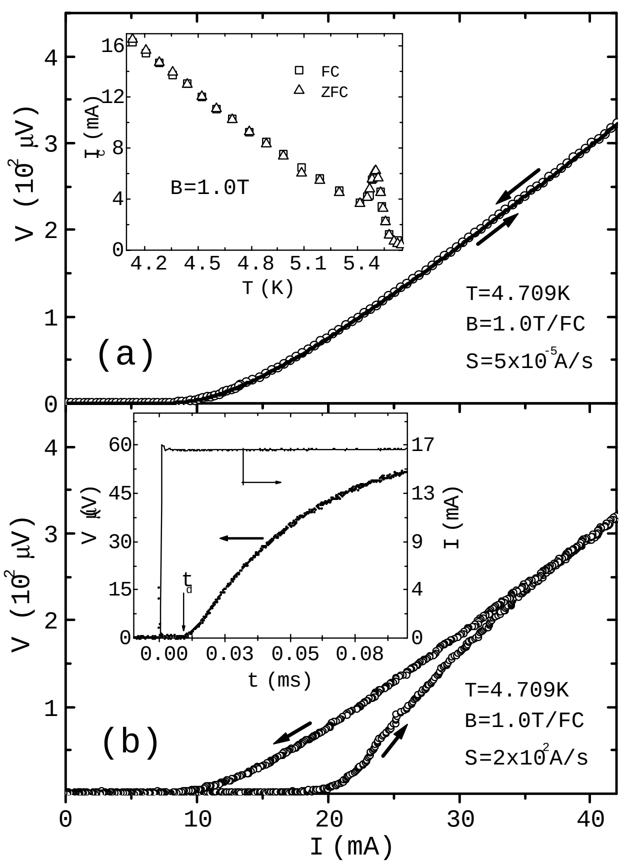


FIG. 1. (a) $I-V$ curves obtained with slow (5x10$^{-}$5A/s) current ramps. The inset shows the temperature dependence of the critical current for ZFC and FC vortex lattices obtained with slow measurements. (b) Fast $I-V$ curves (200A/s) for an FC vortex lattice. The inset shows the time evolution of the response of an FC vortex lattice to a current step.

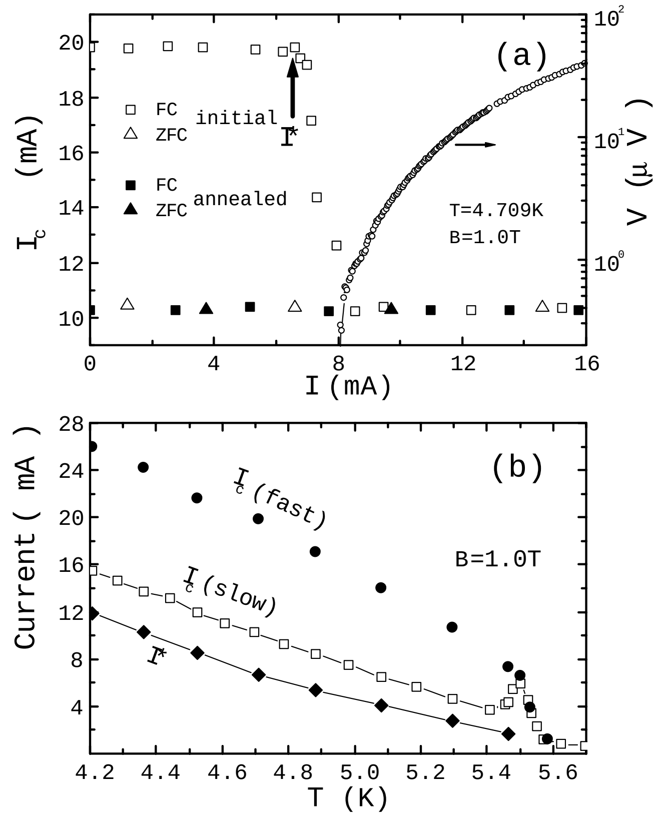


FIG. 2. (a) Critical currents for initial and annealed vortex lattices prepared by ZFC and FC processes following a 100s drive with various currents, $I$. The open circles are the $I-V$ curve of a FC vortex lattice obtained in a slow ($5\times10^{-5}$A/s) measurement. (b) Temperature dependence of critical currents of FC lattice for fast and slow measurements is compared with $I^*$ at various temperatures.

prepared by ZFC and by FC are not identical. In fact, as we show below, the FC lattice is initially in a metastable disordered state which, when driven with a slow current ramp reorganizes into a more ordered configuration indistinguishable from the ZFC state.

That the initial ZFC and FC vortex states are different becomes evident in fast measurements, which probe the system on time scales that are much shorter than the reordering times. This is illustrated in Fig.1 (b) where we compare the fast $I-V$ curve for the pristine FC state, measured on the first ramp-up of the current, with that of the reordered state recorded when the current is ramped down. The critical current of the pristine FC state is almost twice that of the ZFC state indicating that it is more disordered. By contrast the $I-V$ curves of the ZFC state obtained with slow and fast measurements are identical. The pristine ZFC state starts out with a low critical current and exhibits no hysterisis or evolution in its response, which indicates that it is in a stable ordered state. The current driven organization of the FC lattice is seen directly in the inset of Fig.1(b) through the evolution of the response to a current step of fixed amplitude which is below the critiacl current of the FC state. 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.

Next we studied the current dependence of the reorganization. The pristine FC state was driven with long (100sec) current steps and then quenched by suddenly removing the current. The resulting state, for various current amplitudes, was probed by recording a fast $I-V$ curve. In Fig.2(a) we plot the critical current of the quenched state as a function of current-step amplitude. A sharp transition from a disordered state (higher $I_c$) to ordered state (lower $I_c$) is clearly seen at $I^* = 6.7mA$. Also shown are the results for the same experiment carried out on the pristine ZFC lattice and the annealed FC and ZFC lattices. (The vortex lattice was annealed with a slow ($5\times10^{-5}A/s$) cycle of the current between 0 and 50 mA). The absence of a jump in $I_c$ indicates that (at these levels) the current does not cause further ordering of the ZFC or annealed states. Referring to the evolution of the FC state we note that $I^*$ is well below the critical current of the disordered FC state (20mA). This suggests a mechanism in which the conversion from metastable to stable state is nucleated and grows at weak spots in the sample. This process does not in itself produce a detectable voltage signal, but after the ordered phase has grown to form a contiguous channel traversing the sample it will cause a sudden drop in critical current. For higher amplitude current steps, $I > 8mA$ the $I-V$ curves of all quenched states are identical, regardless of the initial state. The transition at $I^*$ was previously seen in 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 the transition at $I^*$ is not the K-V transition but rather a current driven equilibration transition from the metastable disordered FC state to a stable ordered state. The fact that no current driven transition is seen in the the stable ZFC and annealed states again supports this conclusion.

To further illustrate the difference between the equilibration and the current driven crystallization we repeated the above experiment in the lower part of the peak region, where the ZFC state is metastable [5]. In Fig.3(a) we plot the critical current of the quenched vortex state following the application of 100s current steps of various amplitudes. In order to minimize heating at high driving currents the current step was applied in a sequence of short, $10\mu s$, pulses separated by $500\mu s$ cooling intervals with no current. In the following discussion we focus on the data which shows no heating ( star symbols for $I > 10mA$) and will defer the analysis of heating effects till later. In Fig. 3 we show results for FC, ZFC and annealed states. For low currents $I \leq I^* = 4.5mA$ no measurable change occurs in the vortex states. For higher currents, $I^* < I < 8.6mA$ 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 $I$=8.6 mA all the curves converge, overlapping at higher currents as do their respective $I-V$ curves. We conclude that the equilibration transition starts at $I = 4.5mA$ and is completed for $I = 8.6mA$. At higher currents the vortex state is determined by the driving current alone and is independent of the initial preparation. Note that for the highest current steps the critical current attains its lowest value, lower than that of the ZFC state, which indicates motional reordering.

In order to identify the current driven crystallization we focus on the shape of the differential resistance curve shown in Fig. 3(c). The differential resistance becomes

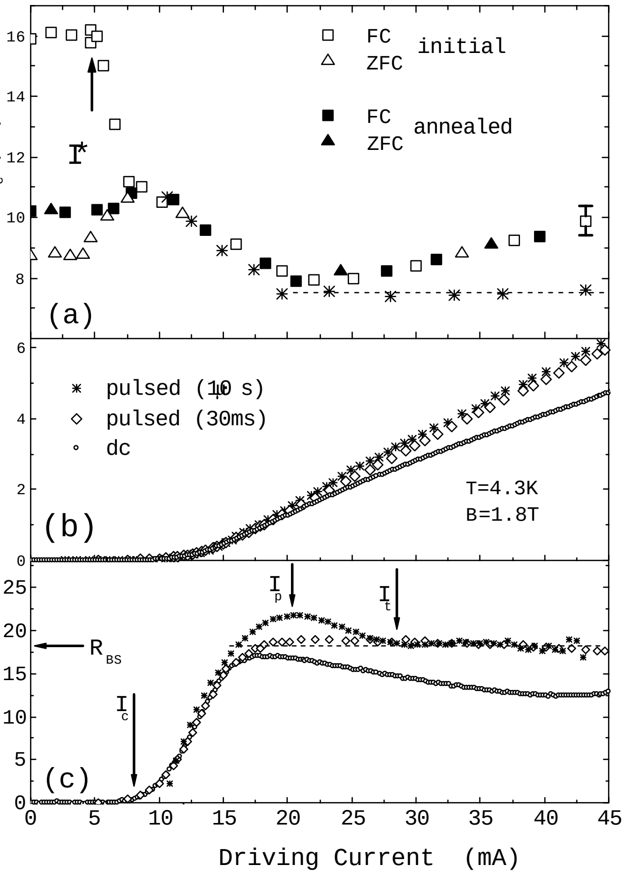


FIG. 3. (a)Evolution of the critical current with driving current for FC and annealed vortex lattice following a 100s drive with continuous currents. $\star$ - data for pulsed current drives. (b) slow $I-V$ curve with DC and pulsed driving current ramps. (c) current dependence of differential resistance illustrating the definition of $I_p$ and $I_t$. The pulsed data saturates at the Bardeen-Stephen free flux flow value.

finite at the same current at which the equilibration transition is complete and metastability has disappeared. As the current is increased the curve rises to a maximum value of $21.7m\Omega$ reached at $I_p = 20.4mA$ and then drops down saturating at the Bardeen-Stephen free flux flow value $R_{BS} = 18m\Omega = R_n H/H_{c2}$ at $I_t = 28.8mA$. Its shape can be interpreted according to recent numerical simulations on the motional organization of a vortex lattice [6,7,12] : 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 into a at $I_t$.

The temperature dependence of $I_t$, shown in Fig.4, is consistent with the KV prediction for the crystallization

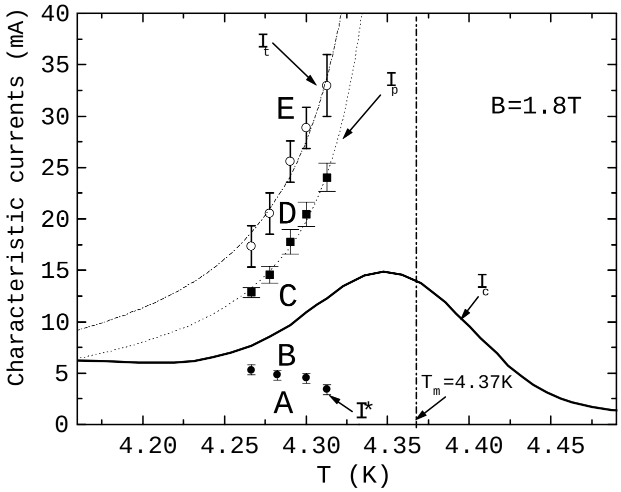


FIG. 4. (a) Temperature dependence of the currents separating the five dynamic regimes: A($I < I^*$) pinned; B($I^* < I < I_c$) equilibration; C($I_c < I < I_p$) plastic flow; D( $I_p < I < I_t$) - smectic ordering, E($I > I_t$)- crystallization. The lines show fits to $I_0/(T_m - T)$ : dotted line - fit with $I_p = 1.34/(4.37{-}T)$; dashed line - fit with $I_t = 1.92/(4.37{-}T)$

with $T_m = 4.37 \pm 0.01K$ the temperature where the pure vortex crystal melts via thermal fluctuations. In the same figure we also show the curves for $I^*$ $I_c$ and $I_t$ which define five dynamic regimes of the moving vortex system: pinned- A; equilibration- B; plastic flow - C; flowing smectic - D and flowing crystal -E.

Transport measurements are prone to heating due to dissipation caused by vortex motion or Joule heating at current contacts. The heating effects are illustrated in Fig 3(a) where the response to continuous currents is compared with that obtained after a sequence of current pulses spaced by appropriate cooling intervals. For states prepared with low amplitude currents ($I \leq 20mA$), $I_c$ is the same for continuous (squares and triangles) and pulsed (stars) applications. At higher amplitudes, heating becomes evident - $I_c$ increases with amplitude for the continuous current steps, whereas it is independent of amplitude in the pulsed method. The increase in $I_c$ in the continuous case reflects the temperature dependence of the peak effect and can be used as a thermometer to quantify the degree of heating. Thus, for a $45mA$ continuous current drive, the sample temperature is $25mK$ higher than for a pulsed current drive, while at $20mA$ it is only $3mK$ higher. Heating at high DC currents is also seen directly in the slow $I-V$ curves shown in Fig3(b). Above $20mA$ the DC curve dips down, reflecting the increase in critical current as the temperature increases. When applying the current ramp in $30ms$ pulses the heating is significantly reduced, and disappears completely for the shorter, $10\mu s$ pulses. This is again seen in Fig3(c) where the dc differential resistance at high currents, is significantly lower than the free flux flow value expected for the KV crystallization transition [7]. We find that heating effects lead to a distorted differential resistance curve which falls below the free flux flow value at high velocities, even though its general shape may still resemble that expected of the KV transition [18,19].

The experiments described here demonstrate the role of the driving current in phase space exploration. Below the peak region we observed a current driven equilibriation transition of the FC lattice. For a metastable state in the lower part of the peak region we identify five dynamic regimes classified by the applied current as shown in Fig 4. For $I < I^*$ the system is unaffected by the current and can remain trapped in metastable states. It is possible that $I^*$ is the current associated with a surface barrier, so that bulk vortices are not subject to a Lorentz force until $I^*$ is exceeded [20,21]. At higher currents, $I^* < I < I_c$, an equilibration transition is observed as the vortices escape out of the metsatble state and, assisted by the current, start exploring the phase space. The stable state is attained at $I_c$, the critical current of the annealed state. Once the equilibration transition is complete the structure of the vortex lattice is solely determined by its velocity. At currents $I > I_c$ the entire lattice starts moving and undergoes motional reordering. Here we distinguish three dynamic regimes starting from plastic flow for $I_c < I < I_p$, through smectic ordering for $I_p < I < I_t$, and finally free flux flow motion attained for $I > I_t$.

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