Flow Induced Organization and Memory of a Vortex Lattice

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We report on the evolution of a vortex state in response to a driving current in $2H$-NbSe$_2$ crystals. By using fast transport measurements we find that the current enables the system to reorganize and access new configurations. During this process the system exhibits a long-term memory: if the current is turned off the vortices freeze in place remembering their prior motion. When the current is restored the motion resumes where it stopped. The experiments provide evidence for a current driven structural change of the vortex lattice and a corresponding dynamic phase diagram that contains a previously unknown regime where the critical current can be either *increased* or *decreased* by applying an appropriate current.

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Vortices in a type-II superconductor exhibit remarkably rich and sometimes surprising collective behavior. The underlying physics is a delicate balance between two competing forces: one is the interaction between vortices, which promotes order, and the other is pinning, caused by randomly distributed material defects, which favors disorder [1–3]. A striking example of this competition is the "peak effect"—a sudden increase in the critical current just below the superconducting transition temperature, T_c, attributed to a structural reorganization when pinning overcomes the ordering influence of interactions [3–6]. Another outcome of this balance is that the vortices are subject to an energy landscape with many metastable states leading to history dependence and nonlinear behavior [4–14]. For example, a vortex array prepared by field cooling, where the magnetic field is applied before cooling through T_c, becomes trapped in a metastable state that is more disordered than one prepared by zero field cooling—where the field is applied after cooling [4,5]. Setting the vortices in motion with an external current releases them to explore the energy landscape and to access new states [7–9], but thus far the dynamics of this process was inaccessible to experiments. To probe the vortex dynamics we have devised a technique that uses fast current ramps and pulses to track the evolution of a vortex lattice as it unpins and starts moving. We find that when the vortices are set in motion they organize into a new state whose properties are determined by the driving current.

The experiments lead to a dynamic phase diagram containing four regimes as a function of increasing current: (A) pinned vortex array at the lowest currents; (B) at higher currents a region of motional reorganization and repinning where the vortices settle into a state whose critical current, I_c, is equal to the driving current; (C) at still higher currents channels of ordered moving vortices cut through domains of disordered stationary ones; (D) at the highest currents all the vortices unpin and form an ordered state.

The vortex motion is detected by measuring the longitudinal voltage across the sample $V = vBl$, where v is the vortex velocity, B is the magnetic field, and l the distance between the voltage contacts. As long as the vortex array is pinned the current flow is dissipationless and only when a critical current density J_c is exceeded, unpinning it, will a voltage appear. For weak pinning superconductors J_c is a measure of the degree of order in the vortex system [3] and, as was confirmed by small-angle neutron scattering (SANS) [15] and transport measurements [5], it is inversely proportional to the size of an ordered vortex domain. Therefore J_c can be used, as was done here, to quantify the degree of vortex order.

The data were acquired on a Fe (200 ppm) doped single crystal of $2H$-NbSe$_2$ of size of $(3 \times 1 \times 0.015)$ mm^3 and $T_c = 5.95$ K. Our measurements employed a standard four probe technique with low resistance contacts made with Ag$_{0.1}$In$_{0.9}$ solder. The current ramps and pulses were generated with a Wavetek 164 and the voltage response was measured with a fast (INA103) amplifier. The current density was obtained by assuming a uniform current distribution [16]. The magnetic field was along the c axis and the current in the a-b plane. All of the data were taken after the sample is zero field cooled (ZFC) [17]. Previous experiments on similar samples revealed novel types of nonlinear behavior including frequency memory and long relaxation times in the lower part of the peak effect region [18]. In the present experiments we find that this is also the region where the value of I_c changes during the measurement.

Figure 1 shows the response to two types of current ramps, fast (FCR—ramping rate of 200 A/s), and slow current ramps (SCR—ramping rate of 1 mA/s). I_c is defined as the current at which the voltage reaches 1 μV. The current-voltage (I-V) curves for FCR and SCR in the inset illustrate the dependence of the response on ramping speed. In particular, the critical current obtained with the

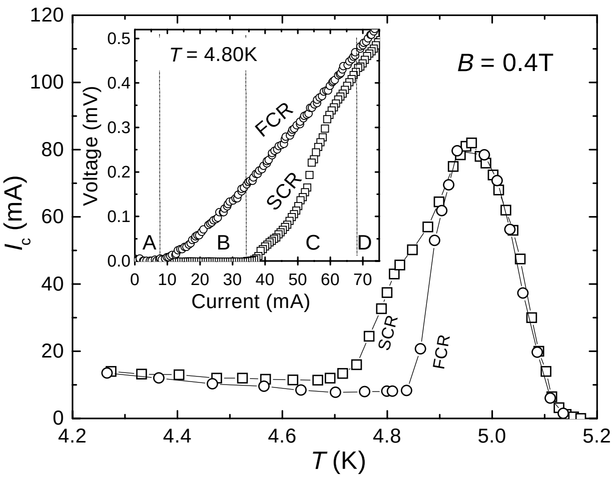

FIG. 1. Temperature dependence of I_c detected by slowcurrent ramps (SCR) and fast current ramps (FCR). Inset: I-V curves in response to SCR (1 mA/s) and FCR (200 A/s). The labels A, B, C, and D illustrate the four regions of the dynamic phase diagram.

FCR, I_{cf}, is lower than I_{cs}, the value obtained for the SCR. The temperature dependence of both I_{cf} and I_{cs} (main panel) exhibits a strong peak effect. The fact that $I_{\mathrm{cf}} \leq I_{\mathrm{cs}}$, for all data points, means that the ZFC state probed by the FCR is always more ordered (the values of I_c give a typical ordered domain size containing $\sim 10^3$ vortices) than the SCR state. This implies that during the SCR the vortex array has time to reorganize into a more strongly pinned state, but the associated vortex motion will not produce a signal if it decays too fast to be resolved.

To observe the reorganization directly we carried out fast measurements with 2 μsec temporal resolution, which enabled us to follow the decay of the response of the ZFC state to a current step $I > I_{\mathrm{cf}}$ as shown in Fig. 2. We note that upon applying the current, the vortex response is instantaneous as expected for overdamped elastic response [19]. As time progresses the voltage decreases despite the fact that the driving current is kept constant. After a sufficiently long waiting time the voltage decays to zero for driving currents in the range $I_{\mathrm{cf}} < I < I_{\mathrm{cs}}$. The decay is also observed for driving currents in excess of I_{cs} indicating that the moving vortex array organizes itself into a less ordered state even though it is not coming to a full stop. In either case the decay proceeds in two steps. On long time scales ($t > 1$ msec) it fits a stretched exponential time dependence $\exp(-t/\tau)^{\alpha}$, where both the characteristic time scale τ and the exponent α depend on current and temperature. This type of slow relaxation is typical of the dynamics in glasses. By contrast, on short time scales ($t < 1$ msec) there is no measurable decay, which is consistent with Lorentz spectroscopy imaging of vortices at the onset of motion [8]. It is this delay before the decay sets in that makes it possible to observe the pristine vortex state—before it has time to reorder—by using a fast current ramp technique.

During the reorganization a striking long-term memory is observed. A typical result is shown in Fig. 3(a) where we plot the response to a current pulse. If the current is interrupted during the decay, the voltage drops to zero instantaneously. When the current is subsequently restored, after a waiting time with zero current, the decay resumes where it stopped the moment the current was turned off and with exactly the same time dependence. In other words the system remembers its state of motion prior to being stopped. The waiting times for which the memory persists can be very long (at least 20 h). Other effects associated with quenching of the vortex motion were observed in experiments on the structure [7,20,21] and transport properties [22].

Long-term memory occurs in systems that can be trapped indefinitely in a metastable state. In the case of vortices this implies that the energy scale of the pinning potential is much larger than that of thermal fluctuations. The current lowers the barriers of the pinning potential and sets the vortices in motion allowing them to settle into a more strongly pinned state. While it is clear that the memory effect in Fig. 3(a) arises because in the absence of current the system is trapped in a metastable state, one can ask what happens if the current is reduced to a finite value rather than removed completely. To explore the interplay between current and pinning we carried out the experiment shown in Fig. 3(b) which repeats the experiment in Fig. 3(a), but after 1.6 msec of applied current, it is reduced to a finite value I_0 for 6 msec, and subsequently restored to the original value. Plotting δV, the voltage decay during the reduced current pulse, as a function of I_0, we find that there is a finite value of I_0 below which the system does not evolve with time. By using the methods described below we find that this value

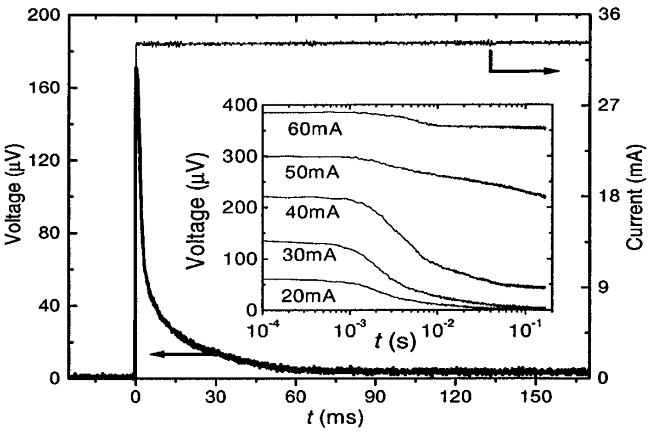

FIG. 2. Time dependence of response to a current step at $T = 4.8$ K and $B = 0.4$ T. The inset shows the response to steps of different amplitudes.

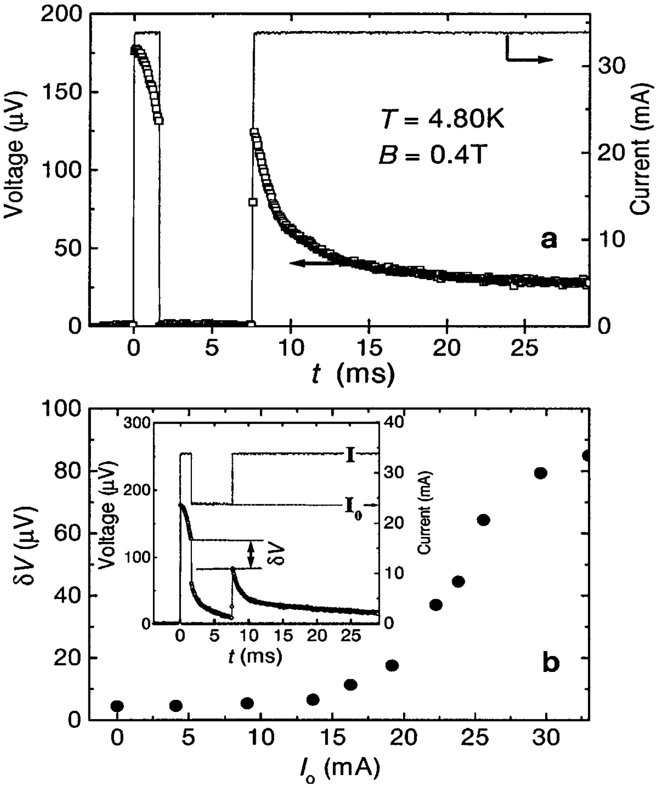

FIG. 3. Memory of a vortex array. (a) During the decay the current is removed and later it is restored to its initial value. The lines and the open squares are the current and the response, respectively. (b) δV as a function of I_0. The definitions of δV and I_0 are shown in the inset.

coincides with the I_c of the vortex state the moment the current was reduced.

The memory effect can be a powerful tool in the study of vortex dynamics. Most probes of the vortex structure require long times to produce one data point or a picture, typically 45 sec in scanning Hall probe microscopy [23] and 15 min in SANS [7]. It would be impossible to observe the reorganization with these techniques. But as our experiments have shown, the vortex structure can be frozen at any moment during its motion by removing the driving current. The quenched vortex system maintains its structure and can then be probed directly. We used this method here to observe the vortex reorganization by quenching the system at various times during its motion and measuring I_c with the FCR method. This was done by preparing a pristine ZFC state and monitoring the decay of the response during an applied current step of duration t_0 [Fig. 4(a), inset]. After the current is removed an FCR is applied to measure the I_c of the vortex state at the moment of current removal [Fig. 4(a), main panel]. By varying t_0 ($t_0 = 0$ gives the I_c of the pristine state) we find that I_c increases with t_0 and saturates at long t_0 [inset of Fig. 4(b)]. In Fig. 4(b) we show the saturation value I_c (reached for $t_0 = 3$ sec) as a function of I. As long as $I_{\mathrm{cf}} < I \leq I_{\mathrm{cs}}$ we find $I_c \sim I$, in other words the system can be prepared with any desired value of I_c in this range by priming it with the appropriate current. For $I > I_{\mathrm{cs}}$, there is an abrupt drop in I_c to a value only slightly above that in the ordered state. We interpret this in terms of the formation of a channel of unpinned and motionally ordered vortices. The fact that I_c is slightly higher than that of the ZFC state may indicate that the motionally ordered state resembles a smectic rather than a crystal [10,11].

We now show that for $I > I_{\mathrm{cs}}$ our data are consistent with channel formation. First we interpret the information contained in the I-V curves: I_c gives the force required to set the vortices in motion and the cordal resistance, defined as $R_c = V/(I - I_c)$, is a measure of the average number of moving vortices in response to a current I. When all of the vortices are moving R_c takes the maximum value, given by the Bardeen-Stephen resistance [24] $R_{\mathrm{BS}} = R_n(\Phi_0/H_{c2})n$, where R_n is the normal state resistance, Φ_0 is the fundamental unit of flux, H_{c2} is the upper critical field, and n is the vortex density. If only a fraction of the vortices move, R_c is reduced proportionately. In the inset of Fig. 1 we note that the cordal resistance for the FCR data, R_c^f, is close to

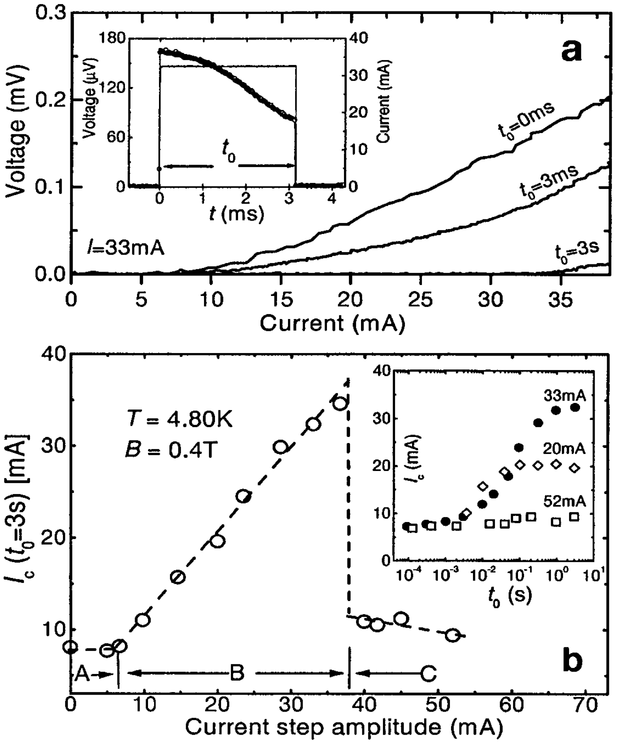

FIG. 4. (a) I-V curves obtained with a fast current ramp following decay periods $t_0 = 0$, 3 ms, and 3 s with current $I = 33$ mA. The definition of t_0 is shown in the inset. (b) I_c obtained at $t_0 = 3$ s and various driving currents. The symbols A, B, and C represent the three regimes of the dynamic phase diagram. The dashed curve is a guide to the eye. Inset: Evolution of I_c with time in the presence of driving currents $I = 20$, 33, and 52 mA.

the maximum value, $R_c^f = 8.75\ \mathrm{m}\Omega = 0.94 R_{\mathrm{BS}}$ which means that essentially all of the vortices are moving. By contrast the I-V curve obtained with the SCR for the same initial vortex state is different: it has a much higher I_c and once the vortex motion is detectable the slope increases with current. In this case the number of moving vortices depends on the current and can be estimated by using the result of Fig. 4(b) that for $I > I_{\mathrm{cs}}$, the moving vortex array is in a state with critical current $\sim I_{\mathrm{cf}}$. Therefore, the ratio of voltage response obtained with the SCR to that obtained with the FCR: $V_s(I)/V_f(I) = R_c^s/R_c^f$ is equal to the ratio of moving vortices in the two measurements. Since in the FCR case the entire array is moving $V_s(I)/V_f(I)$ is in fact a direct measure the fraction of moving vortices. This result leads to the conclusion that for $I_{\mathrm{cs}} < I \leq 2I_{\mathrm{cs}}$ not all of the vortices are participating in the motion and those that do move form channels in which the vortices are ordered (because the critical current is close to I_{cf}), consistent with our assumption. The fraction of moving vortices in the SCR increases gradually from zero at $I = I_{\mathrm{cs}}$ to 1 at $I \sim 2I_{\mathrm{cs}}$ when the channels have engulfed the entire sample forming an ordered state.

Based on these results we identify four regions in the dynamic phase diagram as illustrated in Fig. 1. In region A where $I < I_{\mathrm{cf}}$, the vortex lattice stays pinned and ordered. Region B, where $I_{\mathrm{cf}} < I < I_{\mathrm{cs}}$, is the regime of motional reorganization and repinning. Here the response decays with time as parts of the lattice break loose settling into stronger pinned configurations until the motion comes to a halt when the vortices reach a state with I_c equal to the driving current. This state contains at least one contiguous region of disordered vortices that provides a low resistance current path along the sample. Region C, where $I_{\mathrm{cs}} < I < 2I_{\mathrm{cs}}$, is the plastic flow regime in which channels of moving ordered vortices cutting across the sample are embedded in domains of disordered stationary vortices. In region D, $I > 2I_{\mathrm{cs}}$, the entire vortex array unpins and becomes motionally ordered.

These experiments show that the current (rather than the temperature) plays a central role in assisting the vortex system to choose a configuration in the energy landscape. Applying a current to an ordered state prepared by ZFC lowers the pinning barriers allowing the vortices to find a more strongly pinned state and thus to become more disordered. With increasing current, more of the pinning potential distribution can be explored leading to progressively more strongly pinned states, until at $I > I_{\mathrm{cs}}$ a path forms where vortices reach the edge of the sample without encountering a sufficiently strong pinning center and a channel of motionally ordered vortices can form. We have also shown that at the onset of vortex motion, before reorganization sets in, there is an initial delay during which the system maintains its prior configuration. This initial hesitation together with the long term memory makes it possible to directly probe these processes with transport measurements and in principle with other techniques as well.

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