Metastability and Transient Effects in Vortex Matter Near a Disorder Driven Transition

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We examine metastable and transient effects both above and below the first-order disorder driven decoupling line in a 3D simulation of magnetically interacting pancake vortices. We observe pronounced transient and history effects as well as supercooling and superheating between the ordered and disordered phases. In the disordered supercooled state as a function of DC driving, reordering occurs through the formation of growing moving channels of the ordered phase. We find that hysteresis in $V(I)$ is strongly dependent on the proximity to the decoupling transition line.

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Vortices in superconductors represent an ideal system in which to study the effect of quenched disorder on elastic media. The competition between the flux-line interactions, which order the vortex lattice, and the defects in the sample, which disorder the vortex lattice, produce a remarkable variety of collective behavior \cite{1}. One prominent example is the peak effect in low temperature superconductors, which appears near $H_C$ when a transition from an ordered to a strongly pinned disordered state occurs in the vortex lattice \cite{2,3,4}. In high temperature superconductors, particularly BSCCO samples, a striking "second peak" phenomenon is observed in which a dramatic increase in the critical current occurs for increasing fields. It has been proposed that this is an order-disorder or 3D to 2D transition \cite{2,3,4}.

Recently there has been renewed interest in transient effects, which have been observed in voltage response versus time curves in low temperature superconductors \cite{5,6}. In these experiments the voltage response increases or decays with time, depending on how the vortex lattice was prepared. The existence of transient states suggests that the disordered phase can be supercooled into the ordered region, producing an increasing voltage response, whereas the ordered phase may be superheated into the disordered region, giving a decaying response. In addition to transient effects, pronounced memory effects and hysteretic V(I) curves have been observed near the peak effect in low temperature materials \cite{5,6,7}. Xiao et al. \cite{6} have shown that transient behavior can lead to a strong dependence of the critical current on the current ramp rate. Recent neutron scattering experiments in conjunction with ac shaking have provided more direct evidence of supercooling and superheating near the peak effect \cite{7}. Experiments on BSCCO have revealed that the high field disordered state can be supercooled to fields well below the second peak line \cite{7}. Furthermore, transport experiments in BSCCO have shown metastability in the zero-field-cooled state near the second peak as well as hysteretic V(I) curves \cite{7} and transient effects \cite{8}. Hysteretic and memory effects have also been observed near the second peak in YBCO \cite{9,10}.

The presence of metastable states and superheating/supercooling effects strongly suggests that the order-disorder transitions in these different materials are first order in nature. The many similarities also point to a universal behavior between the peak effect of low temperature superconductors and the peak effect and second peak effect of high temperature superconductors.

A key question in all these systems is the nature of the microscopic dynamics of the vortices in the transient states; particularly, whether plasticity or the opening of flowing channels are involved \cite{8}. The recent experiments have made it clear that a proper characterization of the static and dynamic phase diagrams must take into account these metastable states, and therefore an understanding of these effects at a microscopic level is crucial. Despite the growing amount of experimental work on metastability and transient effects in vortex matter, these effects have not yet been investigated numerically.

In this work we present the first numerical study of metastability and transient effects in vortex matter near a disorder driven transition. We demonstrate that the simulations reproduce many experimental observations, including superheating and supercooling effects, and then link these to the underlying microscopic vortex behavior. We consider magnetically interacting pancake vortices driven through quenched point disorder. As a function of interlayer coupling or applied field the model exhibits a sharp 3D (ordered phase) to 2D (disordered phase) disorder-driven transition \cite{22}. By supercooling or superheating the ordered and disordered phases, we find increasing or decreasing transient voltage response curves, depending on the amplitude of the drive pulse and the proximity to the disordering transition. In the supercooled transient states a growing ordered channel of flowing vortices forms. No channels form in the su-
perheated region but instead the ordered state is homogeneously destroyed. We observe memory effects when a sequence of pulses is applied, as well as ramp rate dependence and hysteresis in the V(I) curves. The critical current we obtain depends on how the system is prepared.

We consider a 3D layered superconductor containing an equal number of pancake vortices in each layer, interacting magnetically. We neglect the Josephson coupling which is a reasonable approximation for highly anisotropic materials. The overdamped equation of motion for vortex \( i \) at \( T = 0 \) is
\[
\dot{\mathbf{r}}_i = -\sum_{j=1}^{N_v} \nabla_i \mathbf{U}(\rho_{ij}, z_{ij}) + \mathbf{f}^{\text{IP}}_i + \mathbf{f}_d = \mathbf{v}_i.
\]
The total number of pancakes is \( N_v \), and \( \rho_{ij} \) and \( z_{ij} \) are the distance between vortex \( i \) and vortex \( j \) in cylindrical coordinates. We impose periodic boundary conditions in the \( x \) and \( y \) directions and open boundaries in the \( z \) direction. The magnetic interaction energy between pancakes is
\[
\mathbf{U}(\rho_{ij}, 0) = 2d\epsilon_0 \left( \frac{1}{2\lambda} \ln \frac{R}{\rho} + \frac{d}{2\lambda} E_1 \right),
\]
\[
\mathbf{U}(\rho_{ij}, z) = -\frac{d^2\epsilon_0}{\lambda} \left( \exp(-z/\lambda) \ln \frac{R}{\rho} + E_2 \right),
\]
where \( R = 22.6\lambda \), the maximum in-plane distance, \( E_1 = \int_0^\infty d\rho' \exp(\rho'/\lambda)/\rho' \), \( E_2 = \int_0^\infty d\rho' \exp(\sqrt{\rho^2 + \rho'^2}/\lambda)/\rho' \), \( \epsilon_0 = \phi_0^2/(4\pi\xi^2) \), \( d = 0.005\lambda \) is the interlayer spacing, \( \lambda \) is the London penetration depth and \( \xi = 0.01\lambda \) is the coherence length. When the magnetic field \( H \) increases, the distance \( \rho \) between pancakes in the same plane decreases, but the distance \( d \) between planes is unchanged. Thus we model \( H \) by scaling the strength of the in- and inter-plane interactions via the prefactor \( s_m \), such that \( s_m \propto 1/H \).

We denote the coupling strength at which the sharp 3D-2D transition occurs as \( s_m^c \). We model the pinning as \( N_p \) short range attractive parabolic traps that are randomly distributed in each layer. The pinning interaction is
\[
\mathbf{f}_{\text{p}}^\text{IP} = \sum_{i \neq j} N_p (f_p/\epsilon_p)(\mathbf{r}_i - \mathbf{r}_j)^{(p)} \Theta((\epsilon_p - |\mathbf{x}_i - \mathbf{x}_j|)/\lambda),
\]
where the pin radius \( \epsilon_p = 0.2\lambda \), the pinning force is \( f_p = 0.02f_0^\ast \), and \( f_0^\ast = \epsilon_0/\lambda \). Throughout this work we will use 16 layers in a 16\( \lambda \times 16\lambda \) system with a vortex density of \( n_v = 0.35/\lambda^2 \) and a pin density of \( n_p = 1.0/\lambda^2 \) in each of the layers. There are 80 vortices per layer, giving a total of 1280 pancake vortices.

For sufficiently strong disorder, the vortices in this model show a sharp 3D-2D decoupling transition as a function of \( s_m \) or \( H \). A dynamic 2D-3D transition can also occur [22]. In the inset of Fig. 1(b) we show the critical current \( f_c^\ast \) and \( z \)-axis correlation \( C_z \) as a function of interlayer coupling \( s_m \), illustrating that a sharp transition from ordered 3D flux lines to disordered, decoupled 2D pancakes occurs at \( s_m^c = 1.2 \). Here \( f_c \) is obtained by summing \( V_x = (1/N_v) \sum_i N_v^2 v_x \) and identifying the drive \( f_d \) at which \( V_x > 0.0005 \), while \( C_z = 1 - \langle |\mathbf{r}_{i,L} - \mathbf{r}_{i,L+1}|/(a_0/2) \rangle \Theta(a_0/2 - |\mathbf{r}_{i,L} - \mathbf{r}_{i,L+1}|), \)

where \( a_0 \) is the vortex lattice constant. The ordered phase has a much lower critical current, \( f_c^\ast = 0.0008f_0^\ast \) than the disordered phase, \( f_c^\ast = 0.0105f_0^\ast \).

To observe transient effects, we supercool the lattice by annealing the system at \( s_m < s_m^c \) into a disordered, decoupled configuration. Starting from this state, at \( t = 0 \) we set \( s_m > s_m^c \) such that the pancakes would be ordered and coupled at equilibrium, apply a fixed drive \( f_d \) and observe the time-dependent voltage response \( V_x \). In Fig. 1(a) we show \( V_x \) for several different drives \( f_d \) for a sample with \( s_m = 2.0 \) in a state prepared at \( s_m = 0.5 \). For \( f_d < 0.0053f_0^\ast \) the system remains pinned in a decoupled disordered state. For \( f_d > 0.0053f_0^\ast \) a time-dependent increasing response occurs. \( V_x \) does not rise instantly but only after a specific waiting time \( t_w \). The rate of increase in \( V_x \) grows as the amplitude of the \( f_d \) increases. As shown in Fig. 1(c), \( C_z \) exhibits the same behavior as \( V_x \).

In Fig. 1(b) we show a superheated system prepared at \( s_m = 2.0 \) in the ordered state, and set to \( s_m = 0.7 \) at \( t = 0 \). Here we find a large initial \( V_x \) response that decays. With larger \( f_d \) the decay takes an increasingly long time. The time scale for the decay is much shorter than the time scale for the increasing response in Fig. 1(a). In the inset of Fig. 1(b) we demonstrate the presence of a memory effect by abruptly shutting off \( f_d \). The vortex
motion stops and when $f_d$ is re-applied $V_x$ resumes at the same point. We find such memory on both the increasing and decreasing response curves. The response curves and memory effect seen here are very similar to those observed in experiments \[7\].

In Fig. 3 we show the vortex positions and trajectories in the supercooled sample with $s_m = 2.0$ from Fig. \[3\](a) for $f_d = 0.007 f_0$ for different times. In Fig. \[3\](a) at $t = 2500$ the initial state is disordered. In Fig. \[3\](b) at $t = 7500$ significant vortex motion occurs through the nucleation of a single channel of moving vortices, which forms during the waiting time $t_w$. Vortices outside the channel remain pinned. In Fig. \[3\](c) at $t = 12500$ the channel is wider, and vortices inside the channel are ordered and have recoupled. The pinned vortices remain in the disordered state. During the transient motion there is a coexistence of ordered and disordered states. If the drive is shut off the ordered domain is pinned but remains ordered, and when the drive is re-applied the ordered domain moves again. In Fig. \[3\](d) for $t = 20000$ almost all of the vortices have reordered and the channel width is the size of the sample. Thus in the supercooled case we observe nucleation of a microscopic transport channel, followed by expansion of the channel.

The vortex positions and trajectories for a superheated sample with $s_m = 0.7$ and $f_d = 0.006 f_0$, as in Fig. \[3\](b), are shown in Fig. \[3\](a-d). In Fig. \[3\](a) the initial vortex state is ordered. In Fig. \[3\](b-d) the vortex lattice becomes disordered and pinned in a homogeneous manner rather than through nucleation. Each vortex line is decoupled by the point pinning as it moves until the entire line dissociates and is pinned.

We next consider the effect of changing the rate $\delta f_d$ at which the driving force is increased on $V(I)$ in both superheated and supercooled systems. Fig. \[3\](a) shows $V_x$ versus $f_d$, which is analogous to a $V(I)$ curve, for the supercooled system at $s_m = 2.0$ prepared in a disordered state. $V_x$ remains low during a fast ramp, when the vortices in the strongly pinned disordered state cannot reorganize into the more ordered state. There is also considerable hysteresis since the vortices reorder at higher drives producing a higher value of $V_x$ during the ramp-down. For the slower ramp the vortices have time to reorganize into the weakly pinned ordered state, and remain ordered, producing no hysteresis in $V(I)$.

In a superheated sample, the reverse behavior occurs. Fig. \[3\](b) shows $V(I)$ curves at different $\delta f_d$ for a system with $s_m = 0.7$ prepared in the ordered state. Here, the fast ramp has a higher value of $V_x$ corresponding to the ordered state while the slow ramp has a low value of $V_x$. During a slow initial ramp in the superheated state the vortices gradually disorder through rearrangements but there is no net vortex flow through the sample. Such a phase was proposed by Xiao et al. \[7\] and seen in recent experiments on BSCCO samples \[10\]. At the slower $\delta f_d$, we find negative $dV/dI$ characteristics which resemble those seen in low-\[24\] and high-\[25\] temperature superconductors. Here, $V(I)$ initially increases as the
vortices flow in the ordered state, but the vortices decou-
le from one another, resulting in an N-shaped characteristic.

To demonstrate the effect of vortex lattice disorder on the critical current, in Fig. 4 we plot the equilibrium $f_c$ along with $f_c$ obtained for the supercooled system, in which each sample is prepared in a state with $s_m = 0.5$, and then $s_m$ is raised to a new value above $s_m$ before $f_c$ is measured. The disorder in the supercooled state produces a value of $f_c$ between the two extrema observed in the equilibrium state. Note that the sharp transition in $f_c$ associated with equilibrium systems is now smooth.

Our simulation does not contain a surface barrier which can inject disorder at the edges. Such an effect is proposed to explain experiments in which AC current pulses induce an increasing response as the vortices reorder but DC pulses produce a decaying response. We observe no difference between AC and DC drives.

In low temperature superconductors, a rapid increase in $z$-direction vortex wandering occurs simultaneously with vortex disordering, suggesting that the change in $z$-axis correlations may be crucial in these systems as well. Our results, along with recent experiments on layered superconductors, suggest that the transient response seen in low temperature materials should also appear in layered materials.

In summary we have investigated transient and metastable states near the 3D-2D transition by supercooling or superheating the system. We find voltage-response curves and memory effects that are very similar to those observed in experiments, and we identify the microscopic vortex dynamics associated with these transient features. In the supercooled case the vortex motion occurs through nucleation of a channel of ordered moving vortices followed by an increase in the channel width over time. In the superheated case the ordered phase homogeneously disorders. We also demonstrate that the measured critical current depends on the vortex lattice preparation and on the current ramp rate.

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