Flux-flow fingerprint of disorder: Melting versus tearing of a flux-line lattice

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A steady-state inhomogeneous flow of a slowly moving flux-line lattice shows the fingerprint of the specific realization of dynamically generated disorder obtained through the interaction between the lattice and the quenched pinning centers. This is characteristic of "tearing" of a soft lattice and is pronounced in a narrow regime of the (H,T) phase diagram where the system is neither a stiff lattice nor a fluid. A first-order depinning transition accompanying this nonequilibrium dynamical phenomenon is fundamentally different from an equilibrium "melting" of a flux-line lattice. A length scale is proposed to describe the dynamics.

Forced collective nonlinear transport in random media[1] represents dynamics of flux-line lattices, charge-density waves, fluid invasion in porous media, Wigner solids in two-dimensional electron gas (2DEG), etc.[2] A basic understanding of the essential features of the dynamics is still lacking. It is assumed that there are two distinct regimes of dynamics, one where the randomness is "weak" and the motion is that of nearly defect-free elastic medium, and the other where the randomness is "strong," the elastic medium is broken up and the transport is highly inhomogeneous.[1] Little is understood experimentally about the systematics of this crossover. The flux-line lattice (FLL) in a clean weak pinning material such as $2H$-$NbSe_2$ serves[3] as an ideal testing ground for the basic phenomena. By tuning the intervortex interaction through the magnetic field one can see[3] this crossover, marked by the peak effect[4] at $H=H_p$ slightly below H_{c2}. Interestingly, thermal fluctuations could not be ignored in this regime either and a thermodynamic melting transition of the FLL may occur in the same part of the phase space. Indeed, a sharp anomaly in the Hall effect at H_p has been interpreted[5] as such. Disentangling results caused by dynamic effects such as discussed here from those caused by thermodynamic effects such as melting is nontrivial.

In this paper we report the observation of a series of anomalous effects in the FLL dynamics including a "fingerprint" phenomenon in the crossover region between weak and strong disorder. Experiments were carried out on single-crystal samples of $2H$-$NbSe_2$ which is a weak-pinning material with experimentally advantageous parameters; $T_c=7.2$ K, $\delta T_c \sim 20$ mK, $R\sim 20$–40, H_{c2} at 4.2 K ~ 2.3 T for $H\|c$ and anisotropy in $H_{c2}\sim 3.3$. Typical sample dimensions are 1 mm $\times 1$ mm$\times 25$ μm. All transport data are taken in the standard four-terminal configuration; low-resistance contacts are obtained with Ag-In solder. The typical critical current density is very small, e.g., $J_c\sim 10$ amp/cm^2 at $H(\|c)=1$ T and $T=4.2$ K, implying a well-formed lattice.[6] A robust peak effect is observed around the reduced field $b(=B/H_{c2})\sim 0.9$ at all values of T and the angle θ between H and the c axis.[3,4]

Figure 1 shows the fingerprint phenomenon. The differential resistance, $R_d(=dV/dI)$, measured from the dc I-V curves are shown in the main panel for different values of $H\perp c$. The inset in (a) shows the variation of the critical current and the pinning force with H. H_{pl} marks the appearance of plastic flow.[3] As the peak regime begins, (for $H_{pl}<H<H_p$), R_d shows jagged peaks at the onset of motion, as in 1(a) for $H=5.6$ T, and decreases to reach a I-independent terminal value consistent with the Bardeen-Stephen (BS) form: $\rho_f=\rho_n(B/H_{c2})$. For the other two field values, $H=4.5$ T, slightly below H_{pl}, as

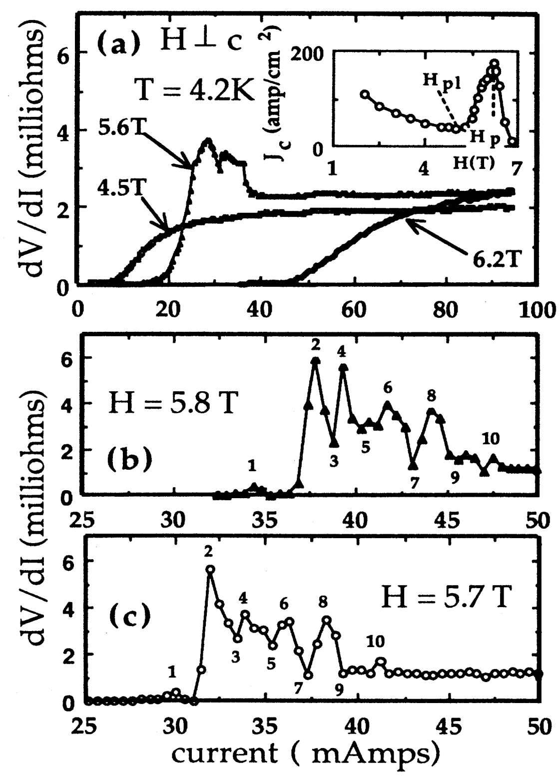

FIG. 1. Variation of the differential resistance obtained from the I-V curves at various fields. The inset in (a) shows the variation of the critical current with H. Note that while the jagged peaks appear for one field they are absent for the other two. Panels (b) and (c) show the fingerprint phenomena in detail. The peak structures are numbered and can be matched from both curves.

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well as for $H = 6.2$ T, coincident with H_p, R_d increases monotonically from zero and no jagged peaks are visible. Subsequently, upon lowering the field down to 5.6 T, the same jaggedness appears, which we call the "fingerprint" of the disorder in the FLL at that value of H.

Examining the fingerprint in more detail, we plot R_d measured with higher current resolution near the onset of flow Figs. 1(b) and 1(c) for two fields differing by 0.1 T and J_c's differing by 15%. In both cases we have numbered the various peaks and valleys for easy identification. Note that features 3, 4, and 5 show a small difference, while the others are nearly unaffected. Thus, the depinning of the FLL proceeds via a series of specific and exactly reproducible jumps (which constitute the "fingerprint") in the I-V curves corresponding to these peaks. Moreover, *the field evolution of the fingerprint* is also observed. We propose that this type of fingerprint is the generic outcome of the breaking up of the FLL and the onset of an inhomogeneous plastic flow[7,8] at the crossover between elastic and fluid flow.

In order to understand the connection between the jagged structures in dV/dI and inhomogeneous flow, we recall that the net voltage in a flux-flow experiment is given by

$$V \sim N_v \langle v \rangle \ , \tag{1}$$

where N_v is the total number of moving vortices and $\langle v \rangle$ is their velocity. For an elastic medium, the entire FLL moves together, i.e., N_v is current independent; thus, $R_d = N_v[d\langle v \rangle /dI]$. The term within the square brackets is proportional to the inverse of the friction coefficient $\mu(v)$. Theoretical work on the dynamics of disordered elastic media is concerned[1,6–9] with the evaluation of $\mu(v)$. Analogy with critical phenomena[1,9] has suggested a power-law scaling form for the I-V curves for a continuous depinning transition: $V \sim (I - I_c)^{\beta}$. Some experimental evidence[10] supporting such scenarios is available for different systems. In all cases, $\mu(v)$ is a smoothly varying function of the driving force as expected from such scaling forms. Indeed, such behavior adequately describes the I-V curves in the present system for the two field regimes that flank plastic flow, i.e., for both $H < H_{\rm pl}$ and $H > H_p$, as shown elsewhere.[3]

Note that the appearance of a jagged structure in R_d, for $H_{\rm pl} < H < H_p$, cannot be due to a jaggedness in $\mu(v)$, since it is clearly unphysical on the basis of known models of dynamics. Thus we attribute the fingerprint to the breakdown of the assumption that N_v is I independent. The depinning occurs in a sequence which violates the elastic media approach to the dynamics and a plastic flow is mandated. In other words, the various peaks and valleys correspond to peaks and valleys in dN_v/dI. For example, the depinning of a large number of vortices in a current interval would yield a peak, followed by a smaller number depinning in the next current interval would yield a valley, and so on. Thus, the jaggedness of R_d is simply related to the fact that the entire FLL does not depin simultaneously at a given critical current, but in a sequence. Thus $\langle v \rangle$ is no longer spatially uniform at small voltages. As I increases, successive depinning occurs for the different chunks. In this case

$$V \sim \sum_j n_j \langle v_j \rangle \ , \tag{2}$$

where the subscript refers to the individual chunks. The contribution of terms such as dn_j/dI to R_d, as new chunks begin to participate in the flow, explains the experimentally observed large values of R_d, greatly exceeding the BS terminal value.

The occurrence of the fingerprint in a narrow field regime can be understood in the following way: The shear modulus of the FLL softens rapidly as the H approaches H_{c2}:

$$C_{66} = (H_{c2}^2/4\pi)(1 - 1/2\kappa^2) b (1-b)^2 (1 - 0.29b)/8\kappa^2 \ .$$

As C_{66} decreases, local strain on the flux lattices due to the quenched disorder grows. As it exceeds the elastic limit in some regions, breakage occurs[8] in the FLL, creating "chunks." A natural description of these chunks is given in terms of a length scale L_v over which the *time-averaged velocity* is correlated. For an elastic medium (i.e., $H < H_{\rm pl}$), even when the instantaneous motion is jerky, the time-averaged velocity is infinitely correlated, i.e., L_v is infinite; hence there are no fingerprints. The onset of plastic flow is given by the finite value of L_v at the onset of motion which measures the size of the chunks. Pronounced fingerprints are obtained when L_v is large, i.e., there are only a few chunks which are sample specific. As H increases, L_v decreases until it equals the lattice spacing a_0 beyond which the chunk is not a meaningful concept and a fluid flow is the appropriate description. In this case (i.e., $H > H_p$), disorder is too strong and the fingerprint is too small to be seen.

In what follows we describe a variety of anomalous results associated with the dynamics in the plastic flow regime. A striking example is an anomalous frequency (ω) dependence of R_d in the peak regime as illustrated in Fig. 2. It is very pronounced at $H = 5.7$ T, while it is negligible at the two other fields. The data establish: (i) an anomalously slow dynamics is associated with plastic flow (due to slow dynamics of dislocations or defects in a soft flux lattice) coincident with the appearance of jagged peaks in dc—R_d; (ii) it occurs at small velocities of the FLL and disappears at larger velocities where the lattice becomes more correlated (and L_v, mentioned above, is also large); and (iii) moreover, R_d for all ω approaches the BS value at these velocities, as expected for a healed FLL.[11]

A further result of the plastic flow is that the moving state is not unique, unlike for an elastic medium.[12] Due to the metastability of the moving state and anomalously slow dynamics of FLL defects, the system becomes noisy[3] as well as history dependent. A specific example is shown in Fig. 3 where the I-V curve is evaluated for a sample in the peak regime. Clearly, the curve is history dependent for I values for which large jumps in V are observed; the higher mobility (larger V) state is retained at smaller I on the decreasing-force (I down) branch. Also note that as I is increased, V can occasionally decrease as well, which is symptomatic of transitions among various "metastable"

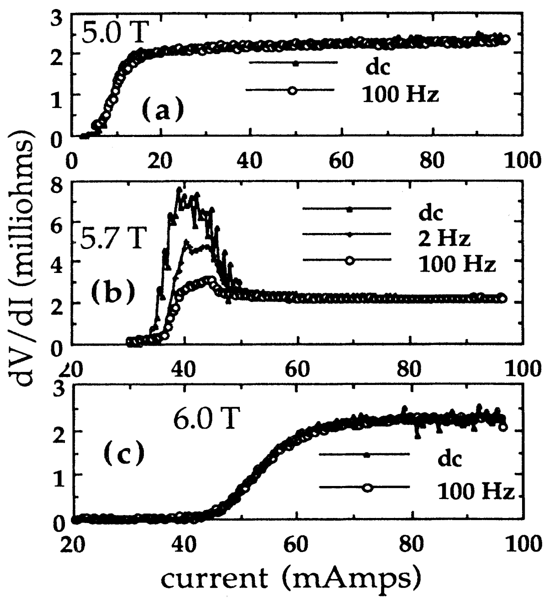

FIG. 2. Anomalous frequency dependence at the onset of motion associated with plastic flow. Note the striking effects at $H = 5.7$ T, while the frequency dependence is absent at both 5 and 6 T.

moving states. These results mark the coexistence of domains with different average velocities, as is implied by the plastic flow of the FLL,[3] which is analogous to the coexistence of ordered and disordered phases in a conventional first-order transition. Thus, in contrast with the behavior conjectured for the defect-free elastic medium, one sees a first-order depinning transition for the defective FLL, as has been conjectured by Coppersmith in a different context.[8] It is indeed interesting to note that they are also remarkably similar to those obtained in the cuprates by changing T or H at a fixed current.[13]

A final example of anomalous dynamics, resulting in a "puddle effect" is shown in Fig. 4. In (a), we show R_d measured at a large bias current at two temperatures, as shown in the inset. The data can be collapsed by plotting the normalized resistance against the reduced field b as shown in the main panel. The functional form is close to,

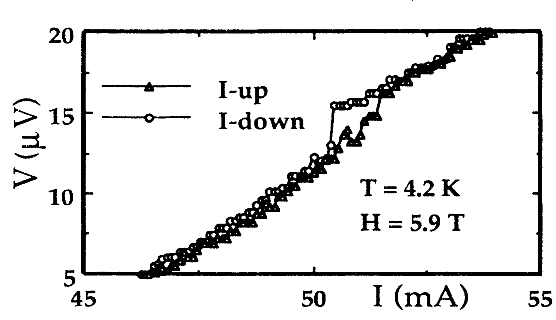

FIG. 3. History dependence of the depinning process in the plastic flow regime. Note the similarity with data in the cuprates as in Ref. 13. See the text for discussions.

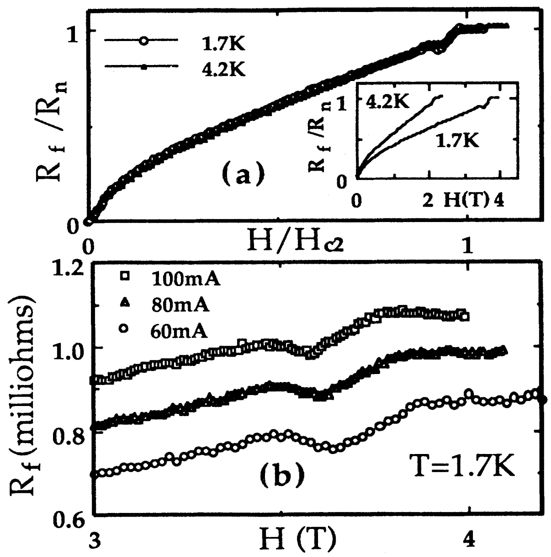

FIG. 4. (a) H dependence of the flux-flow resistance R_f (dV/dI at large I) at two values of T is shown in the inset. The main panel shows the collapse of the data onto a nearly Bardeen-Stephen form when the normalized resistance is plotted against the normalized field b $\{= H/H_{c2}(T)\}$. But the residual kink at H_p is not normalized out. (b) The variation of R_f at three values of driving bias current. I_c is ~ 12 mA. The curves are shifted along the ordinate for clarity. The small shift in H for the kink at larger I is due to a small amount of Joule heating. At the kink, the terminal value of R_f is not reached even at the largest biases although it is reached for H below the kink at the smallest bias. See the text for discussions.

although not identical with, the BS form. In the peak regime, the residual kink from the peak effect does not normalize out. Figure 4(b) shows a series of dV/dI values measured with dc bias current I much larger than I_c. At these values of I, one would expect to find the terminal BS flux-flow resistance. But the residual kink of the peak effect remains visible. Moreover, as the current is increased, there is only a very small effect on the kink. For H slightly below the kink, the terminal behavior is attained at dc bias currents much smaller than what is shown here.

We propose that this is caused by the formation of a puddle of flux lines,[8] and provides circumstantial evidence of a melting of the underlying *clean lattice.* This sample has regions of strong pins, which could be overcome by the interaction among flux lines when the lattice is sufficiently rigid. But as the rigidity disappears due to a presumed melting transition in close proximity of H_p, the strong pins create a puddle of immobile vortices around which flux flow continues. This puddle would require a much larger force in order to be free and to participate in the flow. Inspecting a number of samples we conclude that nearly every sample shows a puddle effect, although their sizes, as obtained from the reduction in R_d, differ from sample to sample, as do the force regime where they are visible. It is in this type of partial flow with steady-state velocity gradients that one may invoke the notion of a flux-line viscosity,[14] in addition to the friction coefficient μ noted above, in order to account for extra damping and the concommitant reduced flow of the vortices.[15]. This provides an extreme example of the absence of coherent motion even at very large forces of what presumably is a flux-line liquid.

In summary, we have demonstrated a series of dynamical anomalies associated with the crossover between elastic and fluid flow through the intermediate plastic flow regime. A length scale L_v is introduced to describe the dynamics in this crossover regime. It would be useful to understand the relationship between L_v and the other two lengths in the problem, the Larkin length R_c (Ref. 6) and the Fisher length (Refs. 1 and 9) ξ_v. The range of dynamics can be summarized by two divergences: (1) a divergence of L_v at the onset of motion in the elastic flow regime as the FLL stiffens and (2) a divergence of the force necessary for a plastic-elastic crossover,[7,8] as the FLL softens or even melts. Note also that L_v is strongly I dependent in the plastic flow regime. As I increases, pinning becomes less important and L_v increases; the plastic-to-elastic crossover[3] at large I is marked by the divergence of L_v and the consequent absence of a fingerprint at large drives.

We conclude with a word of caution. Note that the critical current is strongly dependent on H and T. The effects observed here (in, e.g., Fig. 3) at fixed H and T for varying I, resemble those observed at fixed I and T (or H) for varying H (or T) in the cuprate superconductors.[13] The latter have been attributed to a thermodynamic melting transition, in clear distinction from the purely dynamical effects described here. Since the anomalous dynamics occur for soft lattices in the same part of the (H,T) phase space where a melting transition should occur, a careful comparison of *linear* versus *nonlinear* dynamics is needed to separate the two distinct phenomenologies.

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