Critical behavior at depinning of driven disordered vortex matter in $2H$-NbS_2

Gorky Shaw,[1] Pabitra Mandal,[1] S. S. Banerjee,[1,*] A. Niazi,[2] A. K. Rastogi,[3] A. K. Sood,[4,†] S. Ramakrishnan,[5] and A. K. Grover[5,‡]

[1]*Department of Physics, Indian Institute of Technology, Kanpur 208016, India*
[2]*Department of Physics, Faculty of Natural Sciences, Jamia Millia Islamia University, New Delhi 110025, India*
[3]*School of Physical Sciences, Jawaharlal Nehru University, Delhi 110067, India*
[4]*Department of Physics, Indian Institute of Science, Bengaluru 560012, India*
[5]*Department of Condensed Matter Physics and Materials Science, Tata Institute of Fundamental Research, Mumbai 400005, India*

(Received 29 June 2011; revised manuscript received 4 January 2012; published 15 May 2012)

We report unusual jamming in driven ordered vortex flow in $2H$-NbS_2. Reinitiating movement in these jammed vortices with a higher driving force and halting it thereafter once again with a reduction in drive leads to a critical behavior centered around the depinning threshold via divergences in the lifetimes of transient states, validating the predictions of a recent simulation study [Reichhardt and Olson Reichhardt, Phys. Rev. Lett. **103**, 168301 (2009)] which also pointed out a correspondence between plastic depinning in vortex matter and the notion of *random organization* proposed [Corte *et al.*, Nat. Phys. **4**, 420 (2008)] in the context of sheared colloids undergoing diffusive motion.

DOI: 10.1103/PhysRevB.85.174517 PACS number(s): 74.25.Uv, 74.25.Sv, 74.40.De

I. INTRODUCTION

Dynamical transitions in driven nonequilibrium systems have been considered to exhibit signatures similar to equilibrium critical phase transitions, e.g., the divergence in length or time scales with a characteristic critical exponent.[1–4] Recent simulations and experiments on driven two-dimensional (2D) colloidal systems have shown that the transition from a pinned state to a plastic flow state is associated with diverging time scales[5] along with a characteristic bimodal velocity distribution.[6] The initiation of sliding motion in vortex arrays in type-II superconductors is analogous to the generic *depinning transition* in condensed matter, such as depinning of charge-density waves, colloids, Wigner crystals, magnetic bubbles, magnetic domain walls, etc.[7] A widely investigated nonequilibrium-driven situation in superconducting vortex matter is the plastic depinning of vortices,[7–14] wherein islands of pinned vortices coexist with filamentary channels of freely flowing vortices.

Application of an external transport current normal to the magnetic field gives rise to a Lorentz force which depins the vortex state to reveal a variety of different driven phases, e.g., a moving-ordered Bragg glass state, the plastic flow state, etc.[12–27] Using a new protocol, we have uncovered in a single crystal of a low-T_c anisotropic superconductor, $2H$-NbS_2, two limiting ends of the depinning force, viz., depinning of an ordered *pristine* pinned vortex state (having a lower critical current density J_c^l) and that of a disordered vortex state (having a higher critical current density J_c^h). In the present context, the disordered vortex state gets nucleated as the free flow (FF) in the driven ordered vortex state is *jammed* either by attempting to steadily accelerate or by waiting for a long time. We also report on the discovery of vortex-velocity fluctuating between two extremes near the threshold limit of depinning the jammed, disordered vortex state. The lifetime of the moving state in the fluctuating mode is found to diverge on approaching J_c^h from above as well as below it, validating the prediction of a simulation study,[5] which drew a connection between plastic depinning and the phenomenon of random organization.[4] A few recent experimental studies[26,27] in periodically driven vortex matter pursuing reversible-irreversible transition[28] in periodically driven systems have also explored the above-mentioned connection described in Ref. 5.

II. EXPERIMENTAL DETAILS: ELECTRICAL TRANSPORT MEASUREMENTS IN 2H-NbS_2

The isothermal electrical transport measurements have been performed at $T = 2.5$ K in the standard four-probe geometry, with the dc magnetic field H applied parallel to the c axis of the hexagonal single crystal of $2H$-NbS_2 and with the dc current I flowing in its basal (ab) plane.

The single crystals of $2H$-NbS_2 were grown[29] by the standard vapor-transport technique. The crystal used has the dimensions $0.9 \times 0.9 \times 0.045$ mm^3, with a T_c of 5.8 K and a residual resistivity ratio $R(300\text{ K})/R(10\text{ K})$ of 35. When current I sent thorough a superconductor exceeds the threshold depinning current I_c, a voltage V appears. We use the criterion of the appearance of V of 5 μV to determine I_c. The relationship $V = Hud$, where d is the separation between the voltage contacts (~0.3 mm in the present case), helps in estimating the mean velocity u, with which the vortices drift when $I > I_c$.

III. RESULTS

A. V-H curves at two ramp rates of field: Jamming in driven vortex matter

Figure 1 presents V-H curves with $I = 15$ mA at 2.5 K for two different field ramp rates, $dH/dt(\dot{H})$. Note first that the depinning with a given I (i.e., development of voltage) commences at a lower threshold field of 4 kOe for $\dot{H} = 300$ Oe/min compared to that near 13 kOe for $\dot{H} = 100$ Oe/min (corresponding to $u = 23$ cm/s).[30] The V-H response for $\dot{H} = 100$ Oe/min elucidates that $I_c(H)$ is greater than the applied I of 15 mA for $H < 13$ kOe. After depinning at $H = 13$ kOe, V-H gradually increases to reach its normal-state value at the

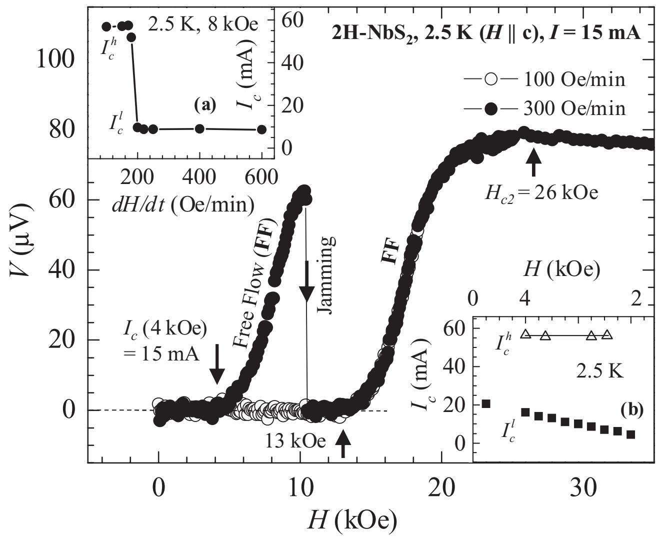

FIG. 1. Voltage drop vs field, V-H, across the single crystal of $2H$-NbS$_2$ for $H \parallel c$ and at 2.5 K for $I = 15$ mA with $\dot{H} = 100$ Oe/min (open circles) and $\dot{H} = 300$ Oe/min (solid circles). The two arrows identify the threshold field values (13 and 4 kOe, respectively) at which $V(H)$ rises above 5 μV. $V(H)$ for $\dot{H} = 300$ Oe/min displays a sudden transition from a high voltage (i.e., moving state) to the nominal zero value (i.e., jammed state) at $H = 10$ kOe ($\ll H_{c2}$). Inset (a) is a plot of I_c vs dH/dt at 8 kOe, and inset (b) displays the variation of I_c^l and I_c^h vs H ($\|c$) at 2.5 K.

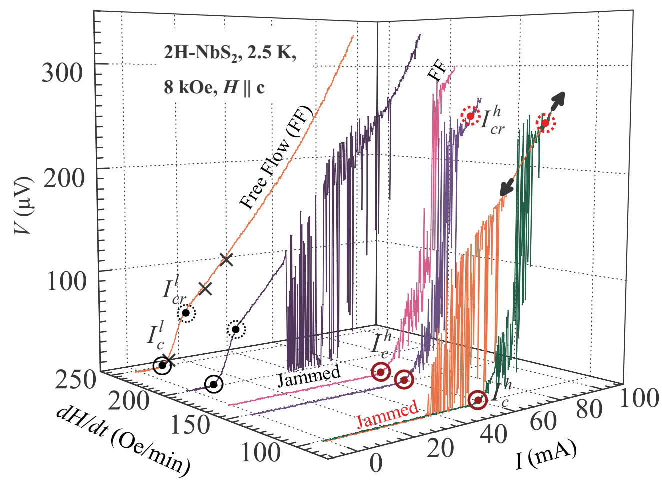

FIG. 2. (Color) The V-I responses in $2H$-NbS$_2$ for some selected vortex states at 8 kOe ($H \parallel c$), prepared via different $\dot{H}$, ranging from 100 to 250 Oe/min. The critical currents I_c^l and I_c^h are identified. The limiting values $I_{\rm cr}^l$ and $I_{\rm cr}^h$, above which V-I curves are quasilinear, are also marked. For a vortex state generated via $\dot{H} = 100$ Oe/min, a reverse leg of the V-I curve has also been shown. The crosses on the V-I curve for $\dot{H} = 250$ Oe/min identify the three current values at which the time series measurements on the voltage are presented in Figs. 3(a)–3(c).

upper critical field H_{c2}. Considering that, while ramping at $\dot{H} = 300$ Oe/min, the depinning with $I = 15$ mA commences at 4 kOe, I_c is $>$ 15 mA only for $H <$ 4 kOe. Thereafter, as $I_c(H)$ progressively decreases further (below 15 mA), the voltage (proportional[12] to a positive power of $[I - I_c(H)]$ continuously enhances from 4 up to 10 kOe, after which the vortex flow is abruptly halted. This corresponds to a dynamic repinning, equivalent to a *jamming* transition in the driven vortex state. The V-H data in Fig. 1 establish that the vortex states prepared with two different $\dot{H}$ have entirely different $I_c(H)$ values for 4 kOe $< H <$ 10 kOe. Above 10 kOe, the two V-H curves in Fig. 1 nearly overlap, and depinning commencing at about 13 kOe and the voltage response thereafter are independent of $\dot{H}$.

B. V-I data for vortex states at a given field generated via different ramp rates

Figure 2 shows a set of V-I curves for vortex states at 8 kOe[31] prepared at 2.5 K via different $\dot{H}$, ranging from 100 to 250 Oe/min. These curves clearly identify two distinct I_c (at $H = 8$ kOe) values, I_c^l and I_c^h, as marked in Fig. 2. Inset (a) in Fig. 1 summarizes the variation of I_c ($H = 8$ kOe) with $\dot{H}$. The higher limiting value I_c^h ($\approx$56 mA) is obtained with $\dot{H} \leqslant 180$ Oe/min, while the lower limit I_c^l ($\approx$ 10 mA) is obtained with $\dot{H} \geqslant 200$ Oe/min.

The V-I curve for the state prepared with $\dot{H} = 250$ Oe/min in Fig. 2 has the usual inflection feature/knee shape[12,13] at $I = I_{\rm cr}^l$; this *crossover* value[13] can be conveniently ascertained from dV/dI vs I (cf. Fig. 14 in Ref. 13). Above $I_{\rm cr}^l$, a quasilinear V-I response sets in (implying a steadily accelerating uniform FF regime), as I is gradually increased to 88 mA. The state prepared with $\dot{H} = 200$ Oe/min also has a low I_c ($\approx$10 mA). However, in its quasilinear flux-flow regime above about 40 mA, it displays very large excursions, with V intermittently dropping to nominal zero, corresponding to jamming of the vortex flow. The fluctuations persist and nearly cease only for $I >$ 75 mA. The presence of fluctuations at $I >$ 60 mA can also be witnessed in the V-I curves for the states prepared with $\dot{H} = 150$ Oe/min, where the initially prepared vortex matter has a higher critical current I_c^h. The higher crossover current limit, at which quasilinear response sets in and large fluctuations in V largely cease, has been denoted by $I_{\rm cr}^h$ ($\approx$83 mA) in Fig. 2. For $\dot{H} = 100$ Oe/min, the V-I data are depicted for I ramped up to about 91 mA and then back down to zero (indicated by the two oppositely directed short, thick arrows in Fig. 2). While ramping down, the V-I curve does not retrace its path below the crossover current $I_{\rm cr}^h$. Larger excursions in V-I during ramp down commence as I is decreased below 56 mA ($=I_c^h$); however, they eventually cease, and the moving vortex state once again reorganizes into the disordered jammed vortex configuration, when $I \sim$ 30 mA. On ramping up the current from zero value for the second time, the depinning commences once again only at the higher critical current I_c^h and not at the lower critical current I_c^l. This observation is in contrast to the finding in weakly pinned $2H$-NbSe$_2$ (Ref. 14) that a vortex state with the lower depinning critical current is nucleated upon halting a steady-flowing state created out of driving a supercooled (i.e., *field cooled*) disordered vortex state with a higher $I_c(H)$.

Inset (b) in Fig. 1 summarizes the variation of I_c^l and I_c^h with H at 2.5 K. Due to collective interaction effects between the vortices, $I_c(H)$ is known to depend inversely[14] on H. The field-dependent lower $I_c^l(H)$ values are thus identified with

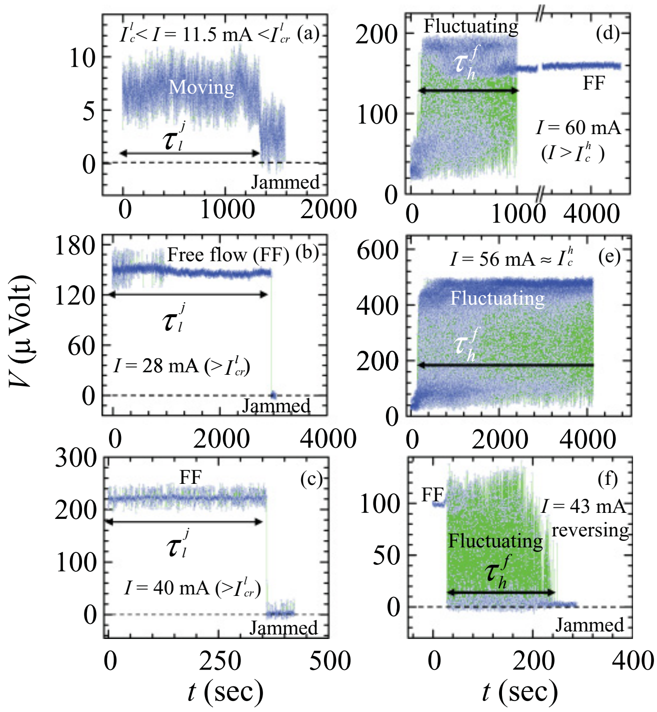

FIG. 3. (Color) Time series measurements (data points shown as blue (open) circles with the symbols joined by green lines) of voltage drop ($\propto$ vortex velocity) at different I in a single crystal of $2H$-NbS_2 at $H = 8$ kOe ($\parallel c$) and $T = 2.5$ K for (a) $I = 11.5$ mA ($> I_c^l$), (b) $I = 28$ mA ($> I_{cr}^l$), (c) $I = 40$ mA, (d) $I = 60$ mA, i.e., just after depinning the jammed/disordered state, (e) $I = 56$ mA ($\approx I_c^h$), i.e., at the threshold of depinning the disordered state, and (f) $I = 43$ mA, i.e., at the reduction of current from the free-flow (FF) state at $I = 91$ mA to $I = 43$ mA. The moving state ($\langle V \rangle$ is greater than 5 μV) can be seen to transform into the jammed state ($\langle V \rangle \sim 2.5$ μV) after a lifetime of τ_l^j in (a)–(c). In (d) and (f) the fluctuating state can be seen to settle down to one of the free-flow or jammed modes after a transient time of τ_h^f. In (e), the fluctuating state seems to persist forever (we recorded data up to about 4100 s). Note also the overshoot of the vortex velocities below zero, i.e., to negative values in different panels.

the ordered vortex matter, and the nearly field independent [up to 10 kOe in inset (b)] higher $I_c^h(H)$ values characterize the *disordered* counterparts[8,14,15] corresponding to independent pinning of small bundles of vortices.

C. Time series measurements for vortex matter driven with different currents

The large fluctuations sampled in the vortex velocity in Fig. 2 motivated us to record the time series of the $V(t)$ response. Figure 3 collates $V(t)$ plots at $H = 8$ kOe (reached via $\dot{H} = 250$ Oe/min after initial zero-field cooling at 2.5 K) for six current values. In Figs. 3(a)–3(c), the initial situation on the average (at $t = 0$) is moving vortex matter (with finite voltage level, above 5 μV), and the eventual condition after a long waiting time τ_l^j (ranging from $\sim 10^2$ to $\sim 10^3$ s) is a jammed state (i.e., $V \leqslant 2.5$ μV). When $I = 11.5$ mA [cf. Fig. 3(a)], the notionally ordered vortex matter having a lower critical current ($I_c^l \sim 10$ mA) is just depinned, and the

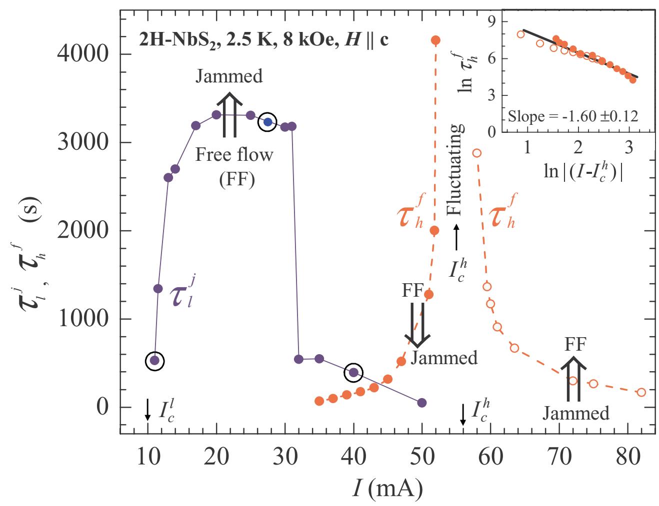

FIG. 4. (Color) Variation of τ_l^j and τ_h^f with current I for vortex states at 8 kOe ($\parallel c$) and $T = 2.5$ K. Three circled data points on the τ_l^j (I) plot represent the typical I values at which the time series data have been displayed in Figs. 3(a)–3(c). The inset shows plots of log τ_h^f vs log $|(I - I_c^h)|$ for two sets of data: $I > I_c^h$ (open circles) and $I < I_c^h$ (solid circles). The straight line amounts to a power law relationship, $\tau_h^f \propto |(I - I_c^h)|^\beta$, with exponent $\beta \approx -1.60 \pm 0.12$.

mean voltage level along with the *average vortex velocity* is small ($\sim$2 cm/s), but after wait time τ_l^j of about 1300 s, the V abruptly drops to the nominal zero level (i.e., <5 μV). In Fig. 3(b), at $I = 28$ mA (greater than crossover current I_{cr}^l), the moving vortex state remains in quasilinear flow mode, with small excursions anchored around $\langle V \rangle \sim 150$ μV, for about 3000 s. However, at $I = 40$ mA [cf. Fig. 3(c)], τ_l^j is only about 350 s.

The τ_l^j values for $I_c^l < I < I_c^h$ are plotted in Fig. 4, and they display nonmonotonic behavior. The progressively faster-moving vortex matter flow reorganizes into a disordered vortex configuration in a shorter time at $I > 30$ mA, with τ_l^j reducing to just about 50 s at $I = 50$ mA. We believe that enhancement in the driving current fuels a competition between the generation of defects,[10,16,21] i.e., dislocations, and their subsequent annealing out in the driven vortex state.[18] One may therefore determine a net rate at which the topological defects, like dislocations, proliferate in the vortex state system. Therefore, τ_l^j is a measure of the drive-dependent time scale needed for a threshold density of defects to build up in the moving lattice at a given field in a given sample,[32] beyond which the stability of the flowing vortex state is significantly compromised (which in the present case occurs beyond 30 mA) and the flow spontaneously reorganizes into the disordered jammed vortex configuration. The vortex-motion-induced crossover to a higher $I_c(H)$ state[33] reported earlier in YNi_2B_2C is notably different from the present result of a sudden change to a disordered state in $2H$-NbS_2 due to similar field dependences of the higher $I_c(H)$ and lower $I_c(H)$ states in YNi_2B_2C. These two field-dependent $I_c(H)$ states in YNi_2B_2C[33] are thus identified with ordered vortex lattices of different symmetries possible to observe in this system.

D. Critical behavior at threshold of de-pinning the jammed state

The disordered configuration realized after a wait time of τ_l^j can be depinned by enhancing the current beyond I_c^h (=56 mA). Figure 3(d) shows $V(t)$ at $I = 60$ mA. Note first that initially (i.e., up to about 50 s), the voltage level rapidly fluctuates between 20 and 60 μV, and thereafter, the upper limit of fluctuations increases to reach about 190 μV. The "state of fluctuation" exists for about 1000 s (marked as τ_h^f), and then suddenly a steady FF [corresponding to $V \sim 160$ μV in Fig. 3(d)] emerges. The τ_h^f measured for different $I (> I_c^h)$ are also plotted (as open circles) in Fig. 4. Note that τ_h^f values decrease rapidly as I progressively increases above I_c^h. The identification of fluctuations and the divergence of τ_h^f as $I \to I_c^h$ in Fig. 4 are two of our key observations. The notion of *divergence* is vividly illustrated in the $V(t)$ plot for $I = 56$ mA in Fig. 3(e). At $I \approx I_c^h$, the large fluctuations in $V(t)$ range between just above zero level (closer to a pinned disordered state) to the high level of about 490 μV. Figure 3(f) shows that vortex matter initially driven into a steady flow with $I = 91$ mA $(> I_c^h)$, when slowed down by decreasing the current to 43 mA $(I < I_c^h)$, maintains its flowing mode at the reduced current only for a short duration (∼30 s). Thereafter, it fluctuates and eventually attains the disordered jammed vortex configuration. $\tau_h^f(I)$ measured for different $I (< I_c^h)$, reduced from an initial current of 91 mA, have also been plotted (as solid circles) in Fig. 4.

Figure 4 shows that τ_h^f diverges from both below and above I_c^h; that is, the back and forth transformation between a steady flowing and a jammed vortex state is through the intervening fluctuating states, whose transient lifetimes diverge upon approaching I_c^h from either side of it.[34] The inset in Fig. 4 shows a fit of the $\tau_h^f(I)$ data to the relationship[5] $\tau \propto |(I - I_c^h)|^\beta$, with $\beta \approx -1.60$ (±0.12) for the disordered vortex matter at 8 kOe at 2.5 K.[31]

IV. CONCLUDING REMARKS

The diverging timescales of large-amplitude fluctuations $\tau_h^f(I)$ in close vicinity of I_c^h suggest that, like a few other nonequilibrium systems, the FF vortex state can undergo a random organization into a pinned disordered configuration, whose depinning attribute is like a dynamical phase transition in a driven nonequilibrium system.[2–5,25] Recent studies suggest that the parameter β, which is akin to a critical exponent,[5] could indicate the notion of universality class for dynamic transitions in diverse types of driven systems. In a different context,[12,13] a case was made for the plastic depinning as a dynamical transition in $2H$-$NbSe_2$ (see Fig. 25 in Ref. 13). However, the present results of characteristic diverging time scales on both sides of the dejamming threshold in $2H$-NbS_2 establish the correspondence between the plastic depinning in the driven vortex state and a (dynamical) random organization occurring between nonfluctuating (pinned or immobile) and fluctuating (flowing) states in driven (diffusive) colloidal systems.[4,5]

The bimodal character of the moving phase fluctuating between two limiting values of the vortex velocities also echoes the behavior reported in the plastic flow regime of driven colloidal crystals[6] and in simulation studies[10] on driven vortex matter. Analysis of the probability distributions of vortex velocities observed by us[35] shows that a fraction of the slower-moving vortices coexist with a faster-moving fraction. The analog of vortex phase fluctuating between two extreme values of vortex velocities was not identified in the context of colloidal matter,[6] which displayed the divergence characteristic in the transient times. We also observe negative values of vortex velocities opposite to the direction of drive (see, for instance, Ref. 35 and cf. Fig. 3) in the disordered jammed vortex state, which justifies the "jammed" nomenclature assigned to the disordered state in $2H$-NbS_2. Similar negative (entropy consuming) events have also been observed and analyzed through the nonequilibrium steady-state fluctuation relation in the sheared jammed state in the surfactant-based hexagonal phase of cylindrical micelles.[36]

ACKNOWLEDGMENTS

Ulhas Vaidya is acknowledged for his help in experiments. S.S.B. acknowledges funding support from the Department of Science and Technology of the government of India.

*satyajit@iitk.ac.in
†asood@physics.iisc.ernet.in
‡grover@tifr.res.in

[1] H. Hinrichsen, Adv. Phys. **49**, 815 (2000).
[2] G. Odor, Rev. Mod. Phys. **76**, 663 (2004).
[3] D. Mukamel, in *Soft and Fragile Matter: Nonequilibrium Dynamics, Metastability and Flow*, edited by M. R. Evans and M. E. Cates (Taylor & Francis, London, UK, 2000), p 237.
[4] L. Corte, P. M. Chaikin, J. P. Gollub, and D. J. Pine, Nat. Phys. **4**, 420 (2008).
[5] C. Reichhardt and C. J. Olson Reichhardt, Phys. Rev. Lett. **103**, 168301 (2009).
[6] A. Pertsinidis and X. S. Ling, Phys. Rev. Lett. **100**, 028303 (2008).
[7] D. S. Fisher, Phys. Rev. B **31**, 1396 (1985).
[8] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).
[9] S. Scheidl and V. M. Vinokur, Phys. Rev. E **57**, 2574 (1998).
[10] M. C. Faleski, M. C. Marchetti, and A. A. Middleton, Phys. Rev. B **54**, 12427 (1996).
[11] E. Olive and J. C. Soret, Phys. Rev. B **77**, 144514 (2008).
[12] S. Bhattacharya and M. J. Higgins, Phys. Rev. Lett. **70**, 2617 (1993).
[13] M. J. Higgins and S. Bhattacharya, Physica C **257**, 232 (1996), and references therein. These authors identified I_{cr} as a crossover current (yielding a crossover force boundary in the dynamical phase diagram in their Fig. 25) and sought support for it from

the simulation of force-velocity curves reported earlier (see Fig. 17 in Ref. 13).

[14] W. Henderson, E. Y. Andrei, M. J. Higgins, and S. Bhattacharya, Phys. Rev. Lett. **77**, 2077 (1996); Z. L. Xiao, E. Y. Andrei, and M. J. Higgins, *ibid.* **83**, 1664 (1999).

[15] S. S. Banerjee, N. G. Patil, S. Saha, S. Ramakrishnan, A. K. Grover, S. Bhattacharya, G. Ravikumar, P. K. Mishra, T. V. Chandrasekhar Rao, V. C. Sahni, M. J. Higgins, E. Yamamoto, Y. Haga, M. Hedo, Y. Inada, and Y. Onuki, Phys. Rev. B **58**, 995 (1998).

[16] T. Giamarchi and P. LeDoussal, Phys. Rev. Lett. **76**, 3408 (1996); P. LeDoussal and T. Giamarchi, Phys. Rev. B **57**, 11356 (1998).

[17] A. M. Troyanovski, J. Aarts, and P. H. Kes, Nature (London) **399**, 665 (1999).

[18] U. Yaron, P. L. Gammel, D. A. Huse, R. N. Kleiman, C. S. Oglesby, E. Bucher, B. Batlogg, D. J. Bishop, K. Mortensen, and K. N. Clausen, Nature (London) **376**, 753 (1995); A. Duarte, E. F. Righi, C. A. Bolle, F. de la Cruz, P. L. Gammel, C. S. Oglesby, E. Bucher, B. Batlogg, and D. J. Bishop, Phys. Rev. B **53**, 11336 (1996).

[19] A. E. Koshelev and V. M. Vinokur, Phys. Rev. Lett. **73**, 3580 (1994).

[20] W. K. Kwok, G. W. Crabtree, J. A. Feindrich, and L. M. Paulius, Physica C **293**, 111 (1997).

[21] Y. Paltiel, E. Zeldov, Y. N. Myasoedov, H. Shtrikman, S. Bhattacharya, M. J. Higgins, Z. L. Xiao, E. Y. Andrei, P. L. Gammel, and D. J. Bishop, Nature (London) **403**, 398 (2000); M. Marchevsky, M. J. Higgins, and S. Bhattacharya, Phys. Rev. Lett. **88**, 087002 (2002).

[22] D. Charalambous, P. G. Kealey, E. M. Forgan, T. M. Riseman, M. W. Long, C. Goupil, R. Khasanov, D. Fort, P. J. C. King, S. L. Lee, and F. Ogrin, Phys. Rev. B **66**, 054506 (2002); D. Charalambous, E. M. Forgan, S. Ramos, S. P. Brown, R. J. Lycett, D. H. Ucko, A. J. Drew, S. L. Lee, D. Fort, A. Amato, and U. Zimmerman, *ibid.* **73**, 104514 (2006).

[23] G. Li, E. Y. Andrei, Z. L. Xiao, P. Shuk, and M. Greenblatt, Phys. Rev. Lett. **96**, 017009 (2006).

[24] S. Mohan, J. Sinha, S. S. Banerjee, A. K. Sood, S. Ramakrishnan, and A. K. Grover, Phys. Rev. Lett. **103**, 167001 (2009).

[25] Y. Fily, E. Olive, N. DiScala, and J. C. Soret, Phys. Rev. B **82**, 134519 (2010).

[26] S. Okuma, Y. Tsugawa, and A. Motohashi, Phys. Rev. B **83**, 012503 (2011).

[27] D. Pérez Daroca, G. Pasquini, G. S. Lozano, and V. Bekeris, Phys. Rev. B **84**, 012508 (2011).

[28] N. Mangan, C. Reichhardt, and C. J. Olson Reichhardt, Phys. Rev. Lett. **100**, 187002 (2008).

[29] A. Niazi and A. K. Rastogi, J. Phys. Condens. Matter **13**, 6787 (2001); A. Niazi, Ph.D. thesis, Jawaharlal Nehru University, 1999.

[30] E. H. Brandt, Phys. Rev. B **52**, 15442 (1995). $\dot{H} = 300$ Oe/min corresponds to vortices crossing the sample edge with $u \sim 69$ cm/s. In IV, similar u ($V = 165\ \mu\text{V} = Hud$ at 8 kOe; cf. IV for the 250 Oe/min curve in Fig. 2) are encountered in the flux-flow regime. Therefore effective quenching from the free-flow regime produces a predominantly ordered state at 8 kOe (300 Oe/min) at 2.5 K.

[31] The vortex state at 8 kOe at 2.5 K is deep inside the mixed state in $2H$-NbS_2 for $H \parallel c$. It is also well below the peak effect phase boundary; see A. A. Tulapurkar, A. K. Grover, S. Ramakrishnan, A. Niazi, and A. K. Rastogi, Physica B **312**, 118 (2003). At 12.5 kOe, which is expected to be located above the onset field of the peak effect at 2.5 K, we find the diverging features in τ_h^f centered around its critical current of 56 mA, similar to those in Fig. 4, with $\beta = 1.4 \pm 0.10$ (data not shown).

[32] *Prima facie*, τ_l^j could depend on the sample shape, size, morphology (i.e., irregularities at edges), etc., as the bundles of vortices entering a sample need time to anneal into an underlying ordered/disordered state. For instance, experiments performed on another rectangular crystal piece of NbS_2, with somewhat irregular edges, revealed that the jammed state while ramping at 300 Oe/min became nucleated at 5 kOe compared to that near 10 kOe for the sample in Fig. 1. The irregularities in the edges accelerate the exploration of the disordered jammed state.

[33] S. Okuma, T. Ichimura, H. Takeya, and K. Hirata, Physica C **469**, 1093 (2009).

[34] Diverging transient times toward acquiring a steady-state flow from the depinning of the plastically deformed states have been reported in the cases of (i) the supercooled (i.e., field cooled) disordered vortex state in $2H$-$NbSe_2$ (Ref. 14) and (ii) above the onset field of the peak effect in a-Mo_xGe_{1-x} films (Ref. 26). However, we are unaware of anything analogous to the vivid fluctuating state(s) present on either side of I_c^h as is being reported in $2H$-NbS_2.

[35] For the analysis of the probability distribution of vortex velocities in $2H$-NbS_2, see http://home.iitk.ac.in/~satyajit/Supplementary_info.pdf, and see J. A. Drocco, C. J. Olson Reichhardt, and C. Reichhardt, Eur. Phys. J. E **34**, 117 (2011) on negative fluctuations.

[36] S. Majumdar and A. K. Sood, Phys. Rev. Lett. **101**, 078301 (2008).