Vortex-state metastability at low-field disorder-order transition

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We report history-dependent critical currents across the disordered solid to Bragg glass transition occurring in the low-field region in V3Si and NdBa2Cu3O7-x single crystals. This is in addition to the history dependence usually observed near the high-field Bragg-glass–disordered-solid transition. It is further shown that the metastable frozen-in disordered vortex matter coexists with the ordered phase in the entire Bragg glass region. We conclude that the amount of the metastable disordered phase prior to the high-field Bragg-glass–disordered-solid transition is crucial in nucleating further growth of the disordered phase near the transition. This mechanism results in the onset of the high-field peak to occur at lower fields when the frozen-in disordered phase prior to the transition is larger.

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In the mixed state of type-II superconductors, just above the first critical field, the intervortex distance is comparable to the London penetration depth. In this low-field regime, pinning is always dominant and a highly disordered flux line lattice is therefore preferred. As the field is progressively increased, a growing intervortex interaction stabilizes the quasiordered Bragg glass phase (Fig. 1). The field where this low-field disorder-order (LF-O/D) transition1,2 occurs depends on the extent of quenched disorder in the superconductor. At further higher fields, Bragg glass phase again undergoes a transition to a highly disordered state.3 This high-field order-disorder (HF-O/D) transition (Fig. 1) is characterized by a sharp increase in critical current density \( J_c \), known as peak effect or second magnetization peak.4,5

The HF-O/D transition is usually accompanied by vortex-state metastability and history dependence in \( J_c \).6–18 In addition, we present experimental results to show the history dependence in \( J_c \) also near the LF-O/D transition. It was recently argued that both the LF-O/D and HF-O/D transitions are first order in nature,2 consistent with observed history effects. There is indeed a growing consensus that it is a quenched-disorder-induced first-order transition of vortex matter.2,15,19,20

The physical mechanism for the metastability in the vicinity of the HF-O/D transition is a subject of current discussion. Paltiel et al.2,23 proposed that the metastable-disordered phase is injected at surface imperfections which dynamically coexist with the stable-ordered phase prior to the transition. Based on our experiments, we shall argue that the presence of a small amount of metastable-disordered phase prior to the transition nucleates the growth of the disordered phase by accumulating more vortices as the field is increased. From our experiments, it appears that this mechanism is predominant over that proposed by Paltiel et al.2,23

Magnetization experiments on a V3Si crystal (1.6 mm \( \times 0.5 \) mm \( \times 0.3 \) mm) with weak pinning (\( T_c = 17 \) K) and a twin-free NdBa2Cu3O7-x (Nd123) crystal (1.4 mm \( \times 0.5 \) mm \( \times 0.2 \) mm) with \( T_c = 95 \) K (Ref. 18) are carried out using an Oxford vibrating sample magnetometer. Nd123 crystal was oriented with its \( c \) axis parallel to the field. V3Si crystal was oriented with the field parallel to its smallest dimension. Figure 2 shows the magnetic moment \( m \) versus field \( H \) in increasing (forward curve) and decreasing (reverse curve) fields for the V3Si sample at 9.5 K (detailed measurements are carried out at this temperature although similar results can be obtained in a wide temperature range) measured with a field sweep rate of 1.2 T/min. Forward curve is measured from a sufficiently large negative field so that induced currents are unidirectional. The initial sharp fall in the magnetization hysteresis (or \( J_c \)) is associated with the disordered solid to Bragg glass transition as discussed above. We identify the HF-O/D transition by the onset (\( H_{on} \)) of a sharp decrease in magnetic moment occurring on the forward curve at around 6 T.3 Such a choice is justified later. The exact location of the transition is, however, controversial due to the occurrence of metastability.

It is common to investigate the history dependent \( J_c \) by means of minor magnetization curves.9–11,13,14,17,18 For instance, near the HF-O/D transition, the minor curves starting on the forward curve (point A in Fig. 2) saturate and do not meet the reverse curve until much lower fields. On the other hand, minor curves starting on the reverse curve (point B in Fig. 2) overshoot the forward curve. As discussed in Ref. 11,
this suggests that \( J_c \) is larger on the decreasing field branch than on the increasing field branch. However, close to the peak position \( H_p \), the minor curves (starting at \( C \) and \( D \)) merge into the main magnetization loop, indicating that \( J_c \) is independent of magnetic history.

In Figs. 3 and 4, we present minor curves in the low-field region (around 1 T) for \( V_3 \)Si and Nd123 samples, respectively. Here, the minor curves starting from the forward curve overshoot the reverse curve [Figs. 3(a) and 4(a)]. On the other hand, the minor curves starting from the reverse curve saturate and do not meet the forward curve until a much higher field [Figs. 3(b) and 4(b)]. This behavior, exactly opposite to that seen near the HF-O/D transition (Fig. 2), is observed over a wide temperature range, for fields above 0.2 T. This behavior of minor curves clearly shows the history-dependent \( J_c \) near the LF-O/D transition; i.e., \( J_c \) is larger on the increasing field branch than on the decreasing field branch. This conclusion is just opposite to that near the HF-O/D transition. As expected, the effect in Nd123 is much weaker than in \( V_3 \)Si, because stronger thermal fluctuations in high-\( T_c \) materials significantly weaken the observable metastability.

The history dependence in \( J_c \) near the HF-O/D transition was recently explained by invoking supercooling\(^{9,11,15,21,22} \) of the high-field disordered solid phase (high \( J_c \)) upon lowering the field below the HF-O/D transition line (path 1 in Fig. 1). Similarly, the quasiordered Bragg glass phase is superheated\(^{15,22} \) by increasing the field above this line.\(^{14} \) Consequently, vortex matter is relatively more ordered (lower \( J_c \)) on the forward curve than on the reverse curve. The terms supercooling and superheating are usually associated with first-order transitions where the free energy has two minima. In the case of the order-disorder transition multiple free energy minima and metastable vortex configurations due to quenched disorder may effectively produce supercooling and superheating effects.

The history-dependent \( J_c \) in the low-field region can be understood in a similar way. Here, the low-field disordered solid phase is superheated upon increasing the field (forward curve) above the LF-O/D line (path 2 in Fig. 1). On the other hand, upon decreasing the field below this line, the Bragg glass phase is supercooled, resulting in a relatively more ordered (thus low \( J_c \)) vortex lattice on the reverse curve than on the forward curve.

\( J_c \) ceases to be history dependent close to the peak field \( H_p \), beyond which only the disordered phase can exist and the ordered phase cannot be present even in the metastable form. Similar arguments apply on the low-field side below a certain field \( H_L \) (about 0.2 T) where \( J_c \) is no longer history dependent. The location of both HF-O/D and LF-O/D transitions is limited by these two fields \( H_p \) and \( H_L \), respectively. The low-field minor curves can be used to determine the field \( H_L \), below which the vortex matter is unambiguously in a disordered equilibrium state.

We now refocus on the minor curves drawn in Fig. 3(b), which do not meet the forward curve up to a field of about 7 T, which is well above \( H_{on} \). Below \( H_{on} \), they are almost parallel, each corresponding to a different metastable state with a specific amount of frozen-in disordered phase. Clearly, the position of the onset seems to be very sensitive to this frozen-in disorder. In the main panel, we show two dotted lines, which are linear extrapolations of the \( m-H \) data (i)
above 5 T on the low-field side and (ii) below 7 T on the high-field side. The intersection point is used as the criterion to determine \( H_{\text{on}} \), the position of HF-O/D transition, on different minor curves. In the inset, \( H_{\text{on}} \) measured on different minor curves is plotted as a function of the \( m \) value at 5.5 T on that minor curve. As shown in the inset, this criterion, used in obtaining \( H_{\text{on}} \), gives a total shift in the transition of about 0.2 T. Alternative criteria—for instance, the field where the \( m \) value changes significantly from an almost constant value below the transition—would give a much higher spread (about 0.6 T) in the transition field. Assuming that the different magnetic moments at 5.5 T are a measure of the different extents of frozen-in metastable disorder prior to the HF-O/D transition, we conclude that the position of the transition shifts to lower fields with increasing amount of frozen-in metastable disorder. Within the mechanism proposed by Paltiel et al.,\(^{23}\) it is hard to imagine how the starting field of the minor curves (for instance at 0.5 and 1.0 T) can affect the disordered phase present at 5.5 T; because, on all the minor curves, new vortices entering the system experience identical conditions at the edges. We propose the following mechanism to understand the shift in the transition field on different minor curves.

Close to \( H_{\text{on}} \), apparently a small amount of metastable disordered phase can nucleate further growth of the disordered phase by accumulating more vortices as the field is increased. The growth is faster when the initial frozen-in disordered phase is larger (or more nucleating sites). In the absence of frozen-in disorder, vortex matter continues to be relatively ordered up to much higher fields, leading to an apparent shift in the onset field to higher values. On the minor curves, the frozen-in metastable disordered phase prior to the transition is smaller and therefore the onset of the peak occurs at higher fields. In other words, the frozen-in disordered phase (nucleating sites) prevents superheating of the ordered phase by triggering the transition, analogous to the case in standard first-order transitions. We may therefore argue that \( H_{\text{on}} \) measured on the forward curve, with a higher amount of frozen-in disorder prior to the transition, is likely to be closer to the real HF-O/D transition.

In the following experiment, we demonstrate the possibility of frozen-in metastable disorder, in the entire Bragg glass region (between LF-O/D and HF-O/D lines), both on increasing and decreasing field branches. It was shown earlier that the metastable-disordered phase can be annealed away or fully eliminated by repeatedly cycling the field by a small amplitude.\(^{14,15}\) The idea is, when the field is cycled, vortices move from their metastable configuration and reorganize into a stable configuration (so-called process of annealing).

Figure 5(a) shows a part of the main hysteresis loop around 5.15 T where magnetization hysteresis is significantly lower than in the peak region as well as in the low-field region (see Fig. 2). We also plot the minor hysteresis loops starting from the forward curve, obtained by repeatedly cycling the field with an amplitude \( \Delta H = 0.1 \) T, which is more than adequate to reverse the induced currents throughout the sample. As shown in Fig. 5(a), the width of the minor hysteresis loop collapses with each successive field cycle and saturates on the loop shown by connected squares. The final width of the loop after several cycles (for clarity some of the loops are omitted) is almost an order of magnitude smaller than the width of the main hysteresis loop at that field. The saturated hysteresis loop obtained is essentially the same even when the minor loops are initiated from the reverse
curve, indicating the existence of a unique stable vortex state.\textsuperscript{14,15}

We show a similar result near 4.05 T in Fig. 5(b), i.e., minor loops starting from the forward curve with repeated field cycling, collapsing to a stable state (again some of the intermediate loops are omitted for clarity). We note that the final saturated loop (shown as solid squares) at 4.05 T is now closer to the reverse curve while at 5.15 T it is closer to the forward curve. This is expected because at 4.05 T, the supercooled metastable phase from above the HF-O/D line (reverse curve) is \textit{annealed} better than at 5.15 T. On the other hand, the superheated disordered phase from the LF-O/D line (forward curve) is more annealed at 5.15 T than at 4.05 T. In conclusion, the stable vortex state in the Bragg glass region is much more ordered than it appears from the width of the main hysteresis loop.

The extent of collapse in the magnetization hysteresis upon field cycling suggests a significant presence of the metastable disordered phase coexisting with the thermodynamically stable Bragg glass phase, both on forward and reverse curves. On the forward curve, the low-field disordered phase (stable below the LF-O/D line) extends deep into the Bragg glass region as a superheated metastable phase. Similarly, the disordered phase, stable above the HF-O/D line, extends deep into the Bragg glass region as a supercooled metastable phase. We further note that upon increasing the field after eliminating the metastable phase by repeated field cycling, $H_{oa}$ is much higher than that on the forward curve. This further supports our point that the amount of \textit{frozen-in} disorder is crucial in determining the onset of the peak effect.

In conclusion, we reported the occurrence of history-dependent critical currents near the low-field disordered–Bragg-glass transition in $V_2$Si and NdBa$_2$Cu$_3$O$_{7-x}$ single crystals. The nature of the history dependence in critical currents near this transition region is just the opposite to that seen near the high-field Bragg-glass–disordered-solid transition. It is also shown that the disordered vortex phase predominantly coexists as a metastable phase in the Bragg glass region with the stable-ordered phase. The onset of the peak effect shifts to lower fields with increasing amount of metastable disordered phase. We conclude that the presence of the disordered phase prior to the Bragg-glass–disordered-solid transition is crucial in nucleating the growth of the disordered phase at the onset of the peak effect. We further argue that the onset field may be closer to the true position of the HF-O/D transition.

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