

Disorder and thermally driven vortex-lattice melting in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ crystals

Y. Radzyner, A. Shaulov, and Y. Yeshurun

Department of Physics, Institute of Superconductivity, Bar-Ilan University, Ramat-Gan, Israel

I. Felner

Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

K. Kishio and J. Shimoyama

Department of Applied Chemistry, The University of Tokyo, Tokyo 113-8656, Japan

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Magnetization measurements in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ crystals indicate vortex order-disorder transition manifested by a sharp kink in the second magnetization peak. The transition field exhibits unique temperature dependence, namely a strong decrease with temperature in the entire measured range. This behavior rules out the conventional interpretation of a disorder-driven transition into an entangled vortex solid phase. It is shown that the transition in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ is driven by *both* thermally- and disorder-induced fluctuations, resulting in a pinned liquid state. We conclude that vortex solid-liquid, solid-solid and solid to pinned-liquid transitions are different manifestations of the same thermodynamic order-disorder transition, distinguished by the relative contributions of thermal and disorder-induced fluctuations.

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The nature of the various vortex matter phases in high-temperature superconductors (HTS), and the transitions between them, have been the topic of many experimental and theoretical investigations.¹⁻¹⁰ Two vortex order-disorder phase transitions have been identified: A melting transition into a liquid vortex state manifested by a discontinuous jump in the reversible magnetization,¹ and a solid-solid transition into an entangled vortex state^{2,3} manifested by the appearance of a second magnetization peak with pronounced features (onset,^{2,3} kink^{5,11} or peak⁴). Theoretical treatments attempting to describe the vortex phase diagram in HTS,⁷⁻¹⁰ ascribe the melting transition to thermal fluctuations and the solid-solid transition to disorder induced fluctuations of vortices. Accordingly, the melting line is determined by the competition between the elastic energy, E_{el} , and the thermal energy, kT , while the contest between E_{el} and the pinning energy, E_{pin} , determines the solid-solid transition line. The melting line is expected to decrease strongly with temperature as thermal fluctuations are enhanced, whereas the vortex solid-solid transition line is expected to maintain a constant value at low temperatures where both E_{pin} and E_{el} become temperature independent. Experiments in a variety of HTS crystals^{2,3,5,6,12} basically conform to this theory, yielding a melting line which decreases with temperature, or a vortex solid-solid transition line which is temperature independent in a wide range of temperatures.

In this paper we report on a significantly different behavior obtained in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LaSCO) crystals. Magnetization measurements reveal a transition of a quasi-ordered vortex lattice into a disordered vortex state with enhanced vortex pinning, indicated by a sharp kink in the second magnetization peak.^{5,11} However, the transition field exhibits a unique behavior, namely strong temperature dependence in the entire measured range. This behavior rules out the conventional interpretation of a transition into an entangled solid

vortex phase in which only E_{pin} and E_{el} play a role. We demonstrate that in order to explain the behavior of the transition line in LaSCO, one must take into account the contribution of thermal energy as well. Thus, our LaSCO samples provide a unique example where the transition to the vortex disordered state is driven by *both* thermally- and disorder-induced fluctuations. The resulting disordered state may be identified as a liquid state with irreversible magnetic behavior, i.e., a vortex pinned-liquid state.¹³

Several samples were cut from a single $(\text{La}_{0.937}\text{Sr}_{0.063})_2\text{CuO}_4$ crystal, with T_c of about 32 K. Data will be shown for sample L1 ($0.8 \times 2.5 \times 0.8$ mm³), though all samples give similar results in all aspects. Magnetization measurements were performed using a commercial superconducting quantum interference device magnetometer (Quantum Design MPMS-5S).

The inset to Fig. 1 presents magnetization loops measured at several temperatures, with the field parallel to the ab planes. Similarly to untwinned $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO),¹⁴ one observes four distinct features (indicated by arrows): The onset of a second peak on the ascending branch at H_{onset}^+ , a sharp change in slope of the magnetization at H_{kink}^+ ,¹⁵ and their counterparts on the descending branch at H_{onset}^- and H_{kink}^- , respectively. The temperature dependence of these features is depicted in the main panel of Fig. 1. Note that all four lines show similar behavior, namely a steep *concave* descent with the increase of temperature. Similar strong temperature dependence of H_{onset}^+ and H_{onset}^- , was observed also for $H \parallel c$. However, for $H \parallel c$, H_{kink}^+ and H_{kink}^- were more difficult to resolve due to the presence of twin boundaries.¹⁶ In this manuscript we therefore focus on results obtained with $H \parallel ab$.¹⁷

Magnetic relaxation measurements yield further insight into the nature of these lines. Figure 2 depicts the evolution of the magnetization at 12 K. In this figure every column

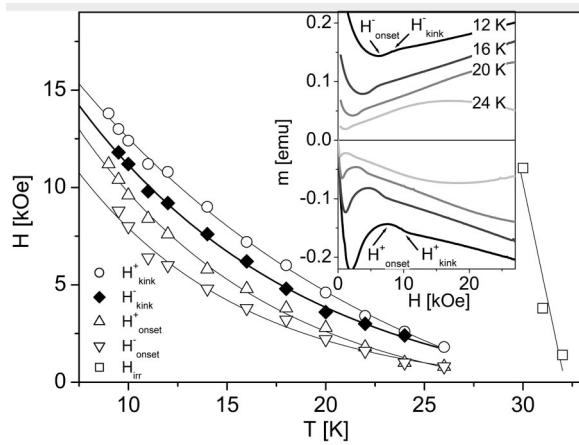


FIG. 1. Temperature dependence of $H_{onset}^+(T)$ (up triangles), $H_{kink}^+(T)$ (circles), $H_{kink}^-(T)$ (solid diamonds), $H_{onset}^-(T)$ (down triangles), and the irreversibility line (open squares). Lines are a guide to the eye. Inset: Magnetization loops with the field parallel to the ab planes, at 12, 16, 20, and 24 K. Arrows point to four characteristic features plotted in the main panel.

represents measurement extended over an hour; the solid lines in the figure connect values obtained at $t=0$ and $t=1$ h. Positions of both H_{kink}^+ and H_{kink}^- (not shown) do not vary with time, while both H_{onset}^+ and H_{onset}^- (not shown) decrease appreciably over an hour. These observations point to either of the kink fields, rather than the onset, as indicating an order-disorder transition, as previously found in YBCO.⁵ This result is further refined by measurements of the field dependence of the normalized magnetic relaxation rate, $s = d(\ln m)/d(\ln t)$, as depicted in the inset to Fig. 2: A sharp change in the slope of s vs field is observed at a field corresponding to H_{kink}^- , on both the branches.¹⁸

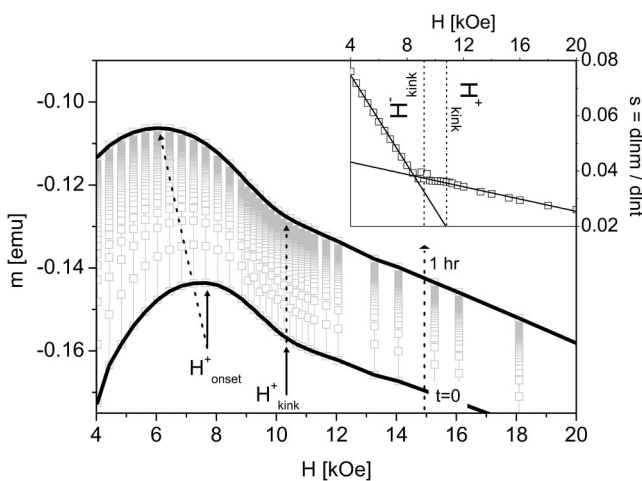


FIG. 2. Relaxation measurements at 12 K, on the ascending branch of the loop. Grey columns represent measurements extended over an hour. Lines connect magnetization at $t=0$ and $t=1$ h. Arrows point at the location of the characteristic features. Note that H_{onset}^+ shifts about 1 kOe, but H_{kink}^+ is unaffected. Inset: Dependence of the relaxation rate on field.

The magnetization curves and relaxation data indicate an order-disorder phase transition of the vortex system occurring at H_{kink}^- , in agreement with observations in YBCO.¹⁴ Since the disordered phase is magnetically irreversible, it is tempting to identify this transition as a vortex solid-solid phase transition, similar to that observed in YBCO,⁵ $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (BSCCO),² $\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_{4-\delta}$,³ and $\text{Bi}_{1.6}\text{Pb}_{0.4}\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$.¹² We note, however, that contrary to these materials, which exhibit a temperature independent solid-solid transition line for a wide range of temperatures, in LaSCO, this line is strongly temperature dependent in the entire measured temperature range. Thus, the conventional interpretation of a disordered-driven transition into an entangled solid phase is refutable.

The measured temperature dependence of the transition line may be influenced by effects of surface barriers, which might obscure the features of the second peak anomaly at low temperatures.^{3,12,14,19} Indeed, magnetization loops in LaSCO reveal a strong temperature dependence of the field where flux initially penetrates the sample overcoming surface barriers.¹⁹ However, Bean-Livingston barriers play a role only in the increasing branch of the loop,²⁰ and have no effect on the decreasing branch; the fact that in LaSCO the strong temperature dependence is common to the features measured on both ascending and descending branches, excludes an explanation associated with surface barriers.

Another possible explanation for the behavior of the measured transition line in LaSCO may be associated with the influence of the persistent current: Strong currents may have a tendency to order the vortices,²¹ so that transition into a vortex glass would be deferred to higher fields. As temperature is decreased current increases, and its influence on the transition line should be marked. This explanation is precluded by the fact that the position of the kink is unaffected by the change in current; as can be seen from Fig. 2, within the time window of the measurement, the current relaxes to about 75% of its initial value, but the position of the kink is not altered, while within the same time window the onset field shifts by about 1 kOe.

In the following, we propose an explanation for the unique temperature dependence of the transition line measured in LaSCO asserting that this transition is driven by *both* thermally- and disorder-induced fluctuations. The transition field at $H_{kink}^-(T)$ is associated with the second magnetization peak, as does the solid-solid transition field, but depends strongly on temperature like the melting field. This strong temperature dependence implies that the transition to the disordered vortex state is driven not only by disorder-induced fluctuations, which are temperature independent far below T_c , but also by thermal fluctuations. As both thermal and disorder-induced fluctuations take a part in destabilizing the ordered solid, the interplay between all three energy scales E_{el} , E_{pin} , and kT , should determine the transition line.^{22–24} The basic premise of our analysis is that an order-disorder transition occurs when the sum of the thermal and the disorder-induced displacements of the flux line, $\langle u_T^2 \rangle$ and $\langle u_{dis}^2 \rangle$, respectively, exceeds a certain fraction of the vortex

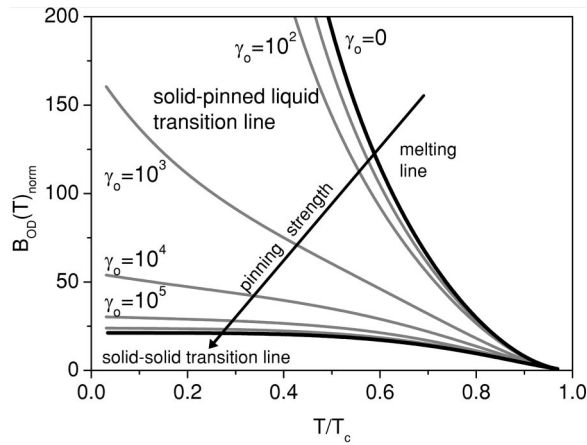


FIG. 3. Numerical solution of $E_{el} = E_{pin} + kT$. The melting (solid-solid transition) line is calculated by neglecting pinning (thermal) energy. All lines in between represent order-disorder transition lines in which both thermal and pinning energies are taken into account, but differ in the pinning strength, γ_o (arbitrary units).

lattice constant,⁷ a_o . This leads to $\langle u_T^2 \rangle + \langle u_{dis}^2 \rangle = c_L^2 a_o^2$ (c_L is the Lindemann number), or equivalently²⁵ to the energy balance at the transition field:

$$E_{el} = E_{pin} + kT. \quad (1)$$

A more accurate analysis should involve the averaged total displacement of the flux line, which is not necessarily the sum of $\langle u_T^2 \rangle$ and $\langle u_{dis}^2 \rangle$. Our simplified analysis yields, however, a qualitative description, and provides important insight.

We numerically solve Eq. (1), using $E_{el} = \varepsilon \epsilon_o c_L^2 a_o$ and $E_{pin} = U_{dp} (L_o/L_c)^{1/5}$ from the cage model.^{8,9} Here, ε is the anisotropy ratio, $\epsilon_o = (\Phi_o/4\pi\lambda)^2$ is the vortex line tension, $U_{dp} = (\gamma \varepsilon^2 \epsilon_o \xi^4)^{1/3}$ is the single vortex depinning energy, $L_o = 2\varepsilon a_o$ is the characteristic length for the longitudinal fluctuations, and $L_c = (\varepsilon^4 \epsilon_o^2 \xi^2/\gamma)^{1/3}$ is the size of the coherently pinned segment of the vortex. The above expressions for E_{el} and E_{pin} are clearly applicable for analyzing our results for $H||c$. We adopt the same expressions also for $H||ab$, assuming that Abrikosov vortices, rather than Josephson vortices, are involved, owing to the small value of the anisotropy, $1/\varepsilon \approx 10-20$.⁶ Also, we assume pinning by point defects, neglecting the intrinsic pinning in between the Cu-O layers, as the angular deviation between different experiments in our setup is larger than the lock-in angle ($\vartheta_L < 1^\circ$).^{10,26,27} Equation (1) was solved numerically, for $\varepsilon = 16\pi^2 \lambda^2 k/\Phi_o^2 c_L^2$ by inserting the explicit temperature dependences of the coherence length $\xi = \xi_o [1 - (T/T_c)^4]^{-1/2}$, the penetration depth $\lambda = \lambda_o [1 - (T/T_c)^4]^{-1/2}$, and the pinning parameter $\gamma = \gamma_o [1 - (T/T_c)^4]^2$.³ This procedure yields the temperature dependence of the order-disorder transition line $B_{OD}(T)$ for different amplitudes of the pinning parameter γ_o , as illustrated in Fig. 3. The “pure” melting line in the figure is obtained by neglecting the pinning energy, so that $E_{el} = kT$, whereas the “pure” solid-solid transition line is obtained by neglecting the thermal energy, i.e., when

$E_{pin} = E_{el}$. All lines in between these two represent order-disorder transition lines in which *both* thermal and pinning energies are taken into account. Thus, by tuning the pinning strength one may gradually change the shape of the transition line and the nature of the disordered phase. In particular, when E_{pin} and kT are comparable, the behavior of the transition line is qualitatively similar to that of a melting line, however it represents a transition to a disordered state exhibiting irreversible magnetic behavior. One may refer to this disordered state as a “pinned liquid state.”¹³ Our experimental results for $B_{OD}(T)$ in LaSCO, see Fig. 1, clearly indicate that our LaSCO sample provides an example of a transition into a vortex pinned liquid state driven by both thermally- and disorder-induced fluctuations.

An indication for the nature of this phase transition was obtained from partial hysteresis loop measurements.^{14,28,29} These partial loops exhibit history dependent phenomena in the region $H_{onset}^-(T) < H < H_{kink}^+(T)$, similar to those obtained in YBCO.¹⁴ The observed history phenomena indicate that a disordered vortex state can be “supercooled” to exist as a metastable state *below* the transition line, i.e., in the region $H_{onset}^-(T) < H < H_{kink}^-(T)$. Likewise, the ordered phase can be “superheated” to exist as a metastable state *above* the transition line, in the region $H_{kink}^-(T) < H < H_{kink}^+(T)$. These observations indicate the first order nature^{14,30} of the transition to the vortex pinned-liquid state. The first order nature of both the melting,¹ and the solid-solid transition,^{14,30,31} was noted previously.

In summary, we observe puzzling temperature dependence of the order-disorder transition field in LaSCO. We show that this behavior may be explained assuming that both thermally- and disorder-induced fluctuations act together in destroying the ordered phase. This approach leads to the conclusion that the melting, solid-solid, and solid to pinned-liquid vortex phase transitions are different manifestations of the same order-disorder thermodynamic first order transition, which, in general, is driven by *both* thermally- and disorder-induced fluctuations. This conclusion is in accordance with several recent works in BSCCO,^{31,32} claiming that the vortex melting line and solid-solid transition line are two manifestations of the same first order transition. Our results show that the behavior of the transition line and the nature of the disordered state are determined by the relative contribution of the disorder-induced fluctuations. When this contribution is negligible (dominates), a transition to a liquid (solid) disordered state is obtained. When the contributions of thermally- and disorder-induced fluctuations are comparable, a transition to a pinned liquid state is obtained. Thus, the observed transition line retains the shape of the melting transition, but the pinning suffices for the transition to be observed as a second peak, and not as a jump in magnetization. The vortex system in LaSCO exhibits such a transition over a wide region of the phase diagram.

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