Possible new vortex matter phases in Bi$_2$Sr$_2$CaCu$_2$O$_8$

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Abstract

The vortex matter phase diagram of Bi$_2$Sr$_2$CaCu$_2$O$_8$ crystals is analyzed by investigating vortex penetration through the surface barrier in the presence of a transport current. The strength of the effective surface barrier and its nonlinearity and asymmetry are used to identify a possible new ordered phase above the first-order transition. This technique also allows sensitive determination of the depinning temperature. The solid phase below the first-order transition is apparently subdivided into two phases by a vertical line extending from the multicritical point.

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The traditional view of type II superconductors was that an ordered solid vortex lattice exists over the entire mixed state phase diagram. For high-temperature superconductors, in contrast, it has been suggested theoretically [1,2], and demonstrated experimentally [3,4], that in clean samples the vortex lattice undergoes a first-order melting transition and thus two phases, vortex solid and vortex liquid, are formed. Recent investigations [5,10], however, have shown that the vortex matter phase diagram is comprised of three distinct phases: a rather ordered lattice at low fields, a highly disordered solid at high fields and low temperatures, and a vortex fluid phase at high temperatures and fields. Such a phase diagram is supported by a number of recent theoretical studies [11,12]. In this letter we show that the phase diagram is even more complex and apparently displays additional new vortex matter phases.

One of the numerous open questions is the structure of the vortex fluid phase, and whether it is further subdivided into two phases: a liquid of vortex lines, and a decoupled gas of vortex pancakes in the CuO planes [13,14]. Both of these fluid phases are weakly pinned, and therefore display high resistivity and reversible magnetization, and thus the existence of a possible transition between them is difficult to resolve. We demonstrate here a new approach for probing such phase transitions. Instead of investigating vortex interaction with the bulk pinning potential, we probe vortex penetration through the surface barrier (SB). It has been shown theoretically that the effective height of the Bean-Livingston SB, and its non-linear dependence on the driving force, depend on whether the vortices are in a solid, liquid, or gaseous state [16,17]. The recently developed technique [18] for measuring the distribution of the transport current across the sample is well suited for investigation of vortex activation over the SB in the presence of a driving force. It also provides valuable information on the bulk transport properties at low fields and temperatures at which the sample resistivity is below the resolution of conventional transport measurements.

Bi$_2$Sr$_2$CaCu$_2$O$_8$ (BSCCO) crystals ($T_c \approx 88$K) were grown using the traveling solvent floating zone method [19]. Silver/gold contacts were evaporated onto freshly cleaved surfaces of single crystals of typical size $150 \times 1500 \times 10 \mu$m$^3$. The crystals were positioned on an
array of seven Hall sensors that measure the perpendicular component of the magnetic field as shown in the inset to Fig. 1. Transport current of 0.5 to 10mA rms (30 - 400 Hz) was applied to the crystal. The resulting self-induced ac field $B_{ac}$ was measured by the sensors using a lock-in amplifier [18]. A constant dc magnetic field of 20G to 5000G was applied parallel to the c-axis. A total of nine crystals were investigated. The characteristic features, which are described below for two typical crystals, were observed in all the samples.

Figure 1d shows the self-field $B_{ac}$ as a function of temperature at a dc field of 1000G. There are three main forms of transport current flow across the width of the sample, depending on the dynamics of vortices [18], as indicated schematically in Figs. 1a-1c. (1a) Vortices are mobile and their drift velocity is determined by bulk viscosity or pinning. In this case the current flows uniformly across the sample, as it does in a normal metal, and $B_{ac}$ decreases monotonically from one edge of the sample to the other (Biot-Savart law). Such flow is observed at $T > T_{sb}$ in Fig. 1d. (1b) Vortices are mobile, but their flow rate across the sample is determined by the low hopping rate over the SB. In this situation most of the current flows at the two edges, where vortices enter and exit the superconductor, in order to provide the necessary driving force to overcome the barrier. Only a very small fraction of the current flows in the bulk to maintain the relatively easy drift of the vortices across the bulk. The resulting self-field distribution inside the sample (sensors 2 - 7) is opposite both in sign and in slope to that for the uniform flow case. This unusual situation [18] is observed over a wide range of temperatures $T_d < T < T_{sb}$ in Fig. 1d. The crossover between the SB and uniform flow occurs gradually over the interval of 60-80K. At the intersection point $T_{sb}$, half of the current flows in the bulk and half at the two edges of the sample [18]. The dashed line in Fig. 2 shows the field dependence of $T_{sb}$. (1c) Vortices are immobile for the given applied current. In this case the transport current distribution has a characteristic Meissner form resulting in $B_{ac} = 0$ within the sample. Such bulk vortex pinning is observed for $T < T_d$. The field dependence of the depinning temperature $T_d$ is shown in Fig. 2.

Figure 1e presents similar data at a lower field of 550G. At fields below 750G another characteristic temperature is present, $T_{FOT}$, at which the first-order phase transition (FOT)
occurs \( T_{\text{FOT}} \). Above \( T_{\text{FOT}} \) practically all the current flows at the edges of the sample. At the transition the relative share of the current in the bulk is suddenly increased, as seen by the drop in the negative self-field signal (linear combination of Fig. 1b with a small contribution of 1a). This indicates that the impedance for vortex flow in the bulk is enhanced, as expected for a liquid-solid transition \[2\]. However, it is important to note that below the transition (i) the vortices are still mobile for all our applied currents, since \( |B_{ac}| > 0 \) within the sample, and (ii) the vortex flow rate is still governed by the SB, since \( B_{ac} \) profile is inverted (with respect to the uniform flow). Vortices become immobile due to bulk pinning at the significantly lower temperature \( T_d \). The field dependencies of \( T_d \) and \( T_{\text{FOT}} \) are shown in Fig. 2. The FOT in this crystal was measured independently by detecting the step in the equilibrium magnetization \[3\] as indicated by the inverted triangles. Figure 2 also shows the position of the second magnetization peak line \( B_{sp} \) obtained on the same crystal using local magnetization measurements \[4\]. We emphasize that the observation of the \( T_d \) line below \( B_{sp} \) is a result of the much higher sensitivity of our technique as compared to transport measurements for which the resistivity below FOT is immeasurably low.

At the FOT, a sharp drop in sample resistance by typically two orders of magnitude is observed \[15,20\]. This drop is usually ascribed to the onset of pinning upon freezing into the solid phase \[3,4\]. The data in Fig. 1e show that in BSCCO the situation is more complicated; both above and below the FOT vortices are mobile and most of the current flows at the sample edges. The drop in measured resistance therefore reflects a sharp increase in the height of the SB. So upon freezing, both the bulk pinning and the SB increase abruptly, but the vortex flow is still dominated by the hopping rate over the SB.

Above the FOT, bulk pinning is very weak and thus is not efficacious as a probe of the state of the vortex matter. Activation over the SB, on the other hand, is predicted to differ significantly between the possible vortex phases \[16,17\]. In particular, the effective height of the barrier increases as the order and the c-axis coherence of the vortex matter increase. For a decoupled gas, for example, the pancakes are individually thermally activated over the barrier and the effective barrier height is low \[16\]. For a liquid of vortex lines, in contrast,
a nucleation loop of a minimum critical size has to be created to allow vortex penetration, resulting in a higher effective barrier \[16\]. In a solid phase, the lattice has to deform in order to accommodate the penetrating vortex, which further increases the barrier height \[17\]. Thus for various processes, the effective barrier height and its non-linear current dependence are different.

Another important property of the SB is the asymmetry between vortex entry and exit. At equilibrium magnetization, the heights of the barriers for vortex entry and exit are identical \[21\]. As a result, in the limit of low transport current in the presence of thermal excitations, the transmission through the barrier is linear with current, and hence the current is equally divided between the two edges of the sample (Fig. 1b). However, due to its asymmetric structure, the barrier height for vortex exit decreases faster with increasing the current as compared to vortex entry \[21,16\]. As a result, at high currents the division between the two edges is unequal, with a larger fraction of the current flowing at the vortex entry edge. For an ac transport current, on the positive half cycle, vortices enter at the left edge and exit at the right (see inset of Fig. 1), and vice versa on the negative half cycle. Accordingly, the current on the left edge will be larger on the positive half cycle and smaller on the negative, resulting in a strong second harmonic signal \(B_{ac}^{2f}\) (Fig. 3a). This is in sharp contrast to bulk pinning which gives rise only to odd harmonics due to the fact that the bulk I-V characteristics, though nonlinear, are symmetric with respect to the current direction \[4\]. The local I-V of SB, in contrast, is asymmetric resulting in even harmonics. The asymmetry between the edges grows with the current, and hence for a given barrier strength \(B_{ac}^{2f}\) is low at small ac currents and high at large currents. Equivalently, for a given ac current a strong barrier results in a low second harmonic whereas a weak barrier gives rise to a large \(B_{ac}^{2f}\). We use this effect to analyze the activation over the SB as follows. Figure 3a shows \(B_{ac}^{2f}\) at 10 mA ac current at 300G and 1000G dc field. For 300G a large \(B_{ac}^{2f}\) is observed at elevated temperatures indicating a relatively weak SB. At \(T_{FOT}\) a discontinuous drop in \(B_{ac}^{2f}\) is observed below which the signal vanishes rapidly. For \(T_d < T < T_{FOT}\) vortex dynamics is dominated by the SB and most of the current flows on the edges, yet \(B_{ac}^{2f}\) is
vanishingly small. As discussed above, this shows that the effective SB increases sharply upon freezing. At fields up to $\sim 400\text{G}$ this SB transition coincides with the FOT. At higher fields, however, we observe a remarkable behavior in which the SB transition follows a new line, labeled $T_x$ in Fig. 2, which resides above the FOT line and extends to elevated fields. Figure 3a shows this SB transition at 1000G. The sharp drop in $B_{ac}^{2f}$ at $T_x$ is very similar to that at $T_{FOT}$ at 300G. In addition, $B_{ac}^{2f}$ is still finite in the range $T_d < T < T_x$ as compared to vanishing $B_{ac}^{2f}$ at 300G. This means that the SB in phase B in Fig. 2 has an intermediate value between the strong barrier in phase E and a weak SB in phase C. Indeed, in the field range 400G to 750G the SB displays two transitions, exemplified below.

An alternative method to investigate the SB is by measuring the first harmonic $B_{ac}$ in the presence of a dc bias current. In the absence of a bias, vortices cross the sample in opposite directions on the positive and negative half-cycles of the ac current. Therefore, on average, each edge carries half of the current. Adding a dc bias breaks this symmetry. Figure 3b shows an example of $B_{ac}$ at 650G due to 4mA ac current with and without bias current of $\pm 6.5\text{mA}$, as measured by sensor 3 which is close to the left edge. At $+6.5\text{mA}$ bias, vortices enter the sample only from the left. Therefore, at any time, the left barrier is larger than the right one and thus more than half of the current is flowing on the left edge. As a result a larger $B_{ac}$ (more negative), as compared to zero bias, is measured by sensor 3. For $-6.5\text{mA}$ bias less than half of the current flows on the left edge and the signal decreases. The degree of splitting between the positive and negative bias curves reflects the strength of the SB. Above $T_x$ the SB is weak and the splitting is large. At $T_x$ the SB is enhanced significantly and the splitting is reduced by about a factor of two. An additional discontinuous drop in the splitting occurs at $T_{FOT}$ due to a further increase of the SB in the solid phase. At fields below 400G the two transitions merge into one FOT.

Discussion. Previous studies of the vortex matter phase diagram in BSCCO have identified three transition lines [7–10] which meet at a multicritical point in Fig. 2: the first-order transition line $T_{FOT}$, the second peak line $B_{sp}$, and the upper depinning line $T_d$ (above $B_{sp}$). The corresponding three phases were interpreted as a highly disordered entangled vortex
solid in phase A, one vortex fluid phase in B and C, and phases D and E as one quasi-lattice or Bragg-glass phase [11,12]. Here we report two additional lines, the $T_x$ line, and the lower $T_d$ line separating the D and E phases (see also Ref. 22). We find that the vortices are mobile in phase E and immobile in phase D. Therefore one possible explanation is that the lower $T_d$ is depinning within the Bragg-glass phase [11,22]. An interesting observation is that this $T_d$ line drops almost vertically down from the multicritical point, and thus, alternatively, it may reflect a recently suggested phase transition line [23]. Accordingly, phase E is a weakly disordered elastic Bragg glass whereas phase D is a strongly disordered Josephson glass [23].

We now discuss the $T_x$ line. Recent flux transformer studies [15] suggest that at high temperatures the FOT is a sublimation transition, and hence phase E is a lattice of vortex lines and phase C is a gas of pancakes. Our results here are consistent with this conclusion showing that phase E is the most ordered and coherent one, whereas phase C is highly uncorrelated. Furthermore, the SB behavior suggests the existence of an additional phase B which has a distinct structure with an intermediate degree of order. An important independent insight into the structure of phase B comes from a recent small angle neutron scattering study [24]. The anisotropy of the BSCCO crystal used in these SANS experiments is very similar to ours, resulting in $T_{FOT}$ and $B_{sp}$ lines [9,24,25] which are practically identical to those in Fig. 2. The earlier SANS data [9] indicated that Bragg peaks are present only in the D and E phases. However a more accurate study demonstrates that the line along which the Bragg peaks disappear follows the FOT line at high temperatures, but then shows an unexpected upturn and continues above the FOT in a “concave” form following our $T_x$ line [24]. Furthermore, at fields above $B_{sp}$ the SANS data show a unique reentrant behavior in which weak but clearly resolvable Bragg peaks are present in the region between $T_d$ and $T_x$ in Fig. 2. For example, Bragg peaks are reported at 900G and 45K [24], indicated by a cross in Fig. 2. These results directly support our conclusion that phase B has a structure with intermediate order between that of phases E and C. Another important feature of phase B is gleaned from the study of very low doses of columnar defects [8]. It is found that the vortex matter loses its shear modulus along the $T_{FOT}$ line rather than along the $T_x$ line. Phase B
therefore has zero or very low shear modulus.

Since Bragg peaks are observable at temperatures above the FOT, phase B cannot be an entangled vortex liquid. One possibility is that this phase is a disentangled liquid of lines, as was proposed to exist in YBCO [14], with some sort of hexatic order that results in weak Bragg peaks. Another possibility is the supersolid [24,27], decoupled solid [13,23], or soft solid [28] phase, which consists of a rather well aligned stack of ordered 2D pancake layers. Such a phase is predicted to have a very low shear modulus due to vortex vacancies or interstitials, and is expected to display Bragg peaks. This interesting scenario implies that the $T_{FOT}$ is a first order-decoupling [13,23,29] or softening [28] transition rather than melting, $T_x$ is melting of the supersolid, and $B_{sp}$ is a disorder induced decoupling [23] rather than a disorder induced solid entanglement [11,12]. Finally, as will be described elsewhere, the $T_d$ line displays some current and frequency dependence, whereas the $T_{FOT}$ and $T_x$ lines do not. It therefore remains to be determined which of the lines in Fig. 2 reflect thermodynamic phase transitions.

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FIGURE CAPTIONS

Fig. 1. Schematics of current distribution \( J \), and corresponding self-field \( B \), of the transport current for (a) uniform current flow, (b) surface barriers, and (c) bulk pinning, with sensor locations indicated. Self-field \( B_{ac} \) induced by 4 mA ac current vs. \( T \) in dc fields of 1000G (d) and 550G (e). Curves are labeled according to sensor number. Inset: Schematic top view of crystal attached to an array of seven Hall sensors. Sensor 1 is outside the sample and the other six span more than half of the sample width.

Fig. 2. BSCCO vortex matter phase diagram. Vortices are immobile in phases A and D. Phase B has an intermediate ordered structure between the ordered lattice in phase E and a pancake gas in phase C. The \( T_x \) line merges with the \( T_{FOT} \) line at low fields. \( T_{sb} \) indicates a crossover from uniform to SB dominated current flow.

Fig. 3. (a) Second harmonic \( B_{ac}^{2f} \) due to SB measured by sensor 3 at 10 mA ac current at 300 and 1000G. The SB is enhanced abruptly below \( T_{FOT} \) and \( T_x \), respectively. (b) First harmonic self-field \( B_{ac} \) at 4 mA ac current and 650G without bias (0) and with positive (+) and negative (-) dc bias of 6.5 mA. The splitting between the + and - curves is reduced at \( T_x \) due to enhancement of the SB. An additional drop in the splitting occurs at \( T_{FOT} \) due to further enhancement of the SB.
Figure 1
Figure 2, Fuchs et al.
Figure 3