SQUID Picovoltometry of Single Crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$: Observation of the Crossover from High-Temperature Arrhenius to Low-Temperature Vortex-Glass Behavior

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Using a SQUID voltmeter we have measured current-voltage curves in untwinned crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ as a function of temperature and magnetic field. Our data show a clear crossover from high-temperature Arrhenius behavior to a critical region associated with the low-temperature three-dimensional vortex-glass phase transition. The critical exponents $\nu(z-1)=7\pm1$ in this system are in accord with theoretical models and previous measurements in $YBa_2Cu_3O_7$. The width of the critical region collapses below 2 T, reflecting the changing role of dimensionality with field.

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The mixed state of a type-II superconductor provides a rare opportunity to explore, in a well-controlled way, the details of a melting transition in the presence of disorder. The Abrikosov crystal, stabilized by long-range interactions, has a lower critical dimension [1] of $d=4$. Experiments in the physical dimension $d=3$, close to the critical value, should produce extreme sensitivity to disorder as well as dimensionality. In a superconductor, disorder enters through random pinning of the vortex lines. Dimensionality can be important in layered materials where the weak coupling between layers can lead to significant quasi-two-dimensional behavior. One manifestation of such behavior will be an enhanced role of thermal fluctuations.

Dissipation in the mixed state occurs through the motion of flux lines or bundles of flux lines. In the simplest model, these are thermally activated over pinning barriers. In this picture, the resistivity is thermally activated, remaining finite at all nonzero temperatures. A significant body of literature [2] has emerged analyzing transport properties of type-II superconductors within this framework of what is essentially a single-particle picture.

In the melting or phase transition picture [3], however, many-body effects are crucially important and must be taken into account in a first-principles way if one is to understand the dynamics of the flux lattice. In this picture, it is assumed that there exists a low-temperature ordered ground state, with a broken symmetry, which undergoes a phase transition into a high-temperature liquid state. A candidate ordered ground state with long-range orientational order has been found in recent decoration experiments [4].

Theories of the phase transition have evolved which include both disorder and dimensionality. Following Ebner and Stroud [5], Fisher, Fisher, and Huse [6] have postulated the existence of a vortex-glass transition. In the vortex-glass phase the vortices are frozen into a particular random configuration determined by the details of the pinning centers in the specific sample. Hence, the vortices are not free to move and the resistivity is strictly zero. Recent measurements on $YBa_2Cu_3O_7$ (YBCO) films [7] and single crystals [8] have provided support for this theory.

In this paper we report measurements of the I-V curves of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) single crystals as a function of temperature and magnetic field. The I-V curves were linear over the temperature and field range studied. We have found a striking crossover from a high-temperature regime in which the resistance is approximately Arrhenius to the low-temperature vortex-glass critical region. We postulate that this crossover occurs at a temperature T^* where the three-dimensional vortex-glass correlation length becomes significant. Above this temperature the flux lines act like two-dimensional pancake vortices, with appreciable correlations only in the planes. Below T^* three-dimensional correlations set in, culminating in a three-dimensional vortex-glass phase transition at T_g. Within a vortex-glass analysis, we find exponents to be roughly field independent and equal to those found in previous measurements on YBCO. We also find that the width of the critical region shrinks abruptly with decreasing field. Below 2 T the transition might become first order.

Our measurements were performed using a modified BTI SQUID voltmeter as described previously [8]. Our apparatus allows us to measure I-V curves with subpicovolt resolution in fields up to 7 T at temperatures from 4 to 100 K. To optimize the measurement of ρ_{xx}, four thin parallel stripes of silver were used as current and voltage contacts. These were evaporated on to the surface soon after cleaving the crystal. The voltage probes were ~1.6 mm apart with ~0.5 mm between them and the current leads. The sample had a width of 3 mm and a thickness of 10 μm. In the data to be presented here, we had a voltage noise of 10 pV/(Hz)$^{1/2}$. System bandwidths were in the range 0.01–0.001 Hz.

The sample used for this experiment is a high-quality single crystal of BSCCO [9]. The unannealed crystal used here exhibited a sharp zero-field resistive transition, with the resistance dropping four decades in 1.5 K. The 10^{-6}-Ω resistance level was reached at 91 K. Magnetization and magnetic decoration experiments [4] indicate bulk superconductivity and very little disorder in the flux lattice. At 100 K the normal-state resistance of our sample was $R_n = 7\times10^{-2}$ Ω which corresponds to a normal-state resistivity of 150 (50) μΩ cm. Resistance measurements were done between 10^{-8} and 10^{-3} Ω. Typical currents used were in the 1-6-mA range which corresponded to current densities at the high end of 10^5 A/m^2, assuming a homogeneous current distribution in the sample. All of the data presented here are linear-response resistance data as a function of temperature and magnetic field with the linear response at all points having been checked over at least two decades in current and voltage.

Shown in the inset in Fig. 1 are Arrhenius plots of the resistance as a function of temperature at fields of 3 and 6 T. As has been suggested before, the resistance is approximately activated with the functional form $\rho(T) = \rho_0 \exp(-U_0/k_BT)$. This functional form can be examined more closely by plotting the data in the form $d(\ln\rho)/d(T^{-1})$ versus temperature. This then becomes a plot of the apparent activation energy U_0 as a function of temperature [10]. The data plotted in this way are shown in Fig. 1. One sees from the data that at high temperatures the apparent activation energy is slowly increasing with decreasing temperature, while between approximately 28 and 40 K the activation energy is roughly constant to within our noise. This slow increase is similar to that found in earlier measurements in this system and has been modeled [3] using the temperature dependences of the underlying superconducting parameters. Thus this model can work reasonably well in fitting data in this regime. However, the ability to parametrize data in this higher temperature regime has no bearing on the question of whether or not there exists a finite temperature phase transition in the high-field mixed state at lower temperatures.

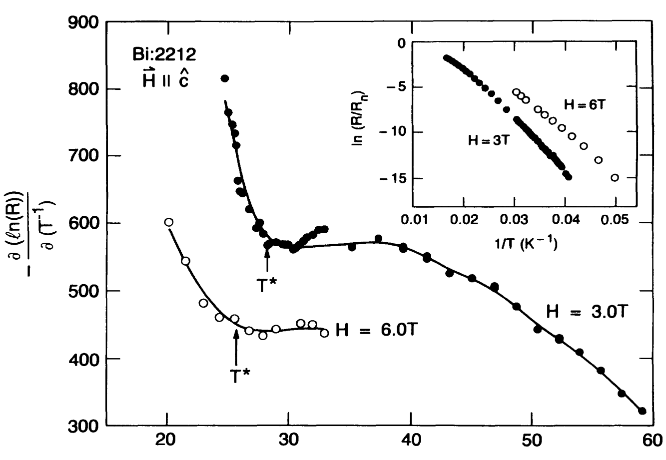

FIG. 1. Temperature dependence of the activation energy U_0 for 3- and 6-T magnetic fields applied parallel to the c axis. $U_0(T)$ is defined as the local slope in the Arrhenius plots, shown in the inset for the same magnetic fields. T^* denotes the beginning of the divergence of U_0. The solid lines are guides for the eye.

Below 28 K the apparent activation energy shows a dramatic and sudden divergence. Clearly, this is the signature of new processes dominating the physics of the vortex lattice dynamics. In YBCO, this divergence of the apparent activation energy occurs near T_c, where the superconducting parameters are still evolving. In contrast, at these low temperatures in BSCCO there should be no remnant temperature dependence to any of the microscopic lengths. Hence, the importance of collective phenomena in the dynamic response of this system becomes manifest.

Shown in Fig. 2 are the low-temperature data at 3 T plotted in a different way. In the scaling regime of the vortex-glass model, the resistance should vanish as $R \sim (T-T_g)^{\nu(z-1)}$. Therefore a plot of $[d(\ln\rho)/dT]^{-1}$ versus temperature should be a straight line with intercept T_g and slope $1/\nu(z-1)$. As shown in Fig. 2 the low-temperature data are consistent with this functional form with a T_g of 20.2 K and slope of 0.17 for the data at 3 T. Shown in the inset in Fig. 2 is the field dependence of the critical exponents extracted from our data using a vortex-glass analysis. There does not appear to be any field dependence to the exponents with the possible exception of the point at 2 T. The values we obtain for $1/\nu(z-1)$ are clustered around 0.15. Previous measurements on single crystal [8] and thick film [7] YBCO samples found $\nu(z-1) = 6.5\pm1.5$ in good agreement with the values presented here. In this type of plot, T^* should be the temperature where the data no longer follow the linear low-temperature behavior characteristic of the critical regime. As can be seen from Fig. 2, this definition is

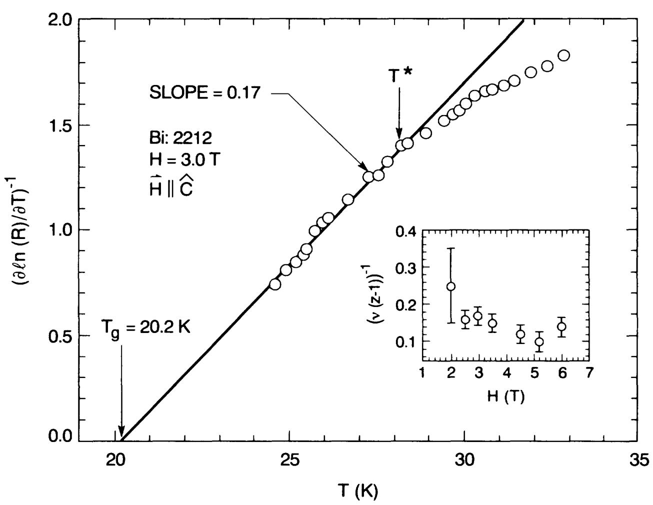

FIG. 2. Plot of the inverse logarithmic derivative of the resistance for the 3-T data. The solid line represents a fit to the vortex-glass theory with $T_g = 20.2$ K and $[\nu(z-1)]^{-1} = 0.17$. Deviations from the vortex-glass model are observed above 28 K, indicating the crossover to a noncritical regime. Inset: Critical exponents for different fields. The value and large errors for $H = 2$ T are strongly affected by the shrinking of the critical region at low fields.

consistent with the temperatures for T^* as extracted from the Fig. 1 data [11].

We understand the data in Fig. 1 in the following way. At high temperatures, while there may be significant two-dimensional correlations *in* the planes, there is little correlation between planes. As the temperature decreases these two-dimensional correlations will grow. Despite these increasing correlations, the dynamics may still be dominated by thermal activation, as the effective barriers produced by the growth of the two-dimensional correlations are likely to be small in comparison to the pinning energy for single flux lines. However, the system will cross over to three-dimensional behavior as the three-dimensional vortex-glass correlation length ξ_{3D} grows. This should [6] occur when $(\xi_{3D}/a_0)^2=(\lambda/d)$, where a_0 is the vortex lattice spacing and d is the interplane spacing. Our data do not allow the numerical values for ξ to be extracted. Nonetheless, a crude estimate of this crossover suggests it is likely to occur near $T\sim 2T_g$. This is because the estimates for both T_g and T^* arise from the same arguments, with only numerical differences. We suggest that T^* is this crossover temperature. Below T^*, the dynamics will contain an important contribution from the critical fluctuations associated with the incipient three-dimensional vortex-glass phase transition.

The absence of nonlinearities in our data provides a clue to the crossover from thermal activation to critical behavior. The three-dimensional vortex-glass correlation length $\xi_{3D}=81.6\ \mu\text{m}(T/J)^{1/2}$ defines when the measuring current affects the thermal vortex distribution. For linear response, this length must be larger than the vortex-glass correlation length. As the correlation length diverges, the current will thus decrease to zero. In an anisotropic system, the correlations will be likewise anisotropic, with $\xi_{ab}\xi_c=(\xi_{3D})^2$. In the two-dimensional case this reduces to $\xi_{2D}d=(\xi_{3D})^2$. In the high-temperature limit, the two-dimensional correlation length is the appropriate one to consider.

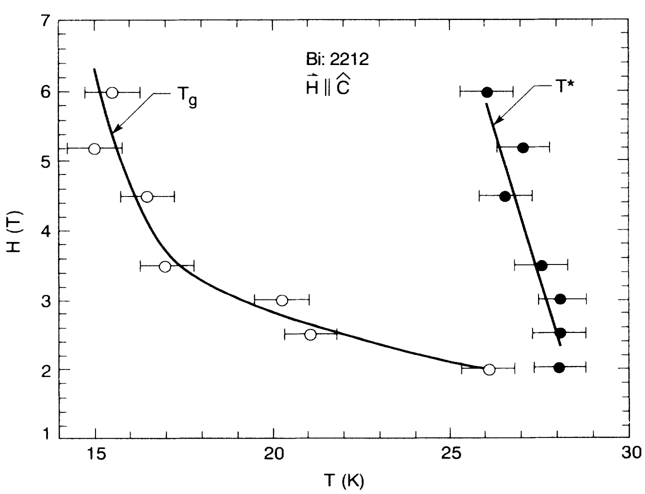

FIG. 3. Magnetic phase diagram, where T_g represents the glass transition. T^* marks the crossover to a low-temperature regime dominated by 3D cooperative effects. Typical error bars are shown, while the solid lines are simply guides for the eye.

Because of the extreme anisotropy, the current in our measurement is likely to flow in only a few conducting planes. Indeed, the anisotropy ρ_c/ρ_a has been shown [12] to increase dramatically with decreasing temperature in the mixed state. With $T=50$ K and a maximum current of 5 mA $\xi_{2D}<1\ \mu$m, assuming the current is confined to a single layer. A more uniformly distributed current only serves to raise this upper bound. At 6 T, ξ_{2D} could then be as large as $50a_0$, implying a well-ordered lattice in the planes. These long-range two-dimensional correlations are consistent with our hypothesis that T^* reflects the point at which three-dimensional correlations start to become important.

Shown in Fig. 3 is the phase diagram for T_g and T^* as a function of magnetic field. The region between T_g and T^* is the vortex-glass critical region which is quite large at high fields. In contradistinction to YBCO, the scaling region in BSCCO becomes extremely broad at high fields, approaching 10 K at 6 T. This width, implying $\Delta T/T_g\sim 1$, is much greater than would be expected for a normal critical region. In YBCO, we found [8] $\Delta T/T_g=0.05$, a more traditional value. At low fields the critical region becomes vanishingly small. The data shown in Fig. 3 suggest that below 2 T the transition might become first order as the critical region vanishes. This coincides with a relative sharpening of the transition. This is plausible as one might expect pinning to become more important at higher fields. As an example for why this might happen, in this field regime the flux lattice positional correlation length has been calculated by Fisher, Fisher, and Huse [6] and they find that it goes as T^2/B. Their basic argument is that thermal fluctuations will smear out the pinning forces at higher temperatures and reduce their effectiveness in disordering the lattice. At lower fields, the transition occurs at higher temperatures, therefore the disorder should be less important and the transition might become first order, as was suggested for measurements in clean YBCO crystals [13]. Unfortunately our sensitivity is such that we are unable to probe this region with our picovoltmeter. Other probes such as magnetization and heat capacity may be sensitive to the transition in this regime.

The extreme anisotropy of BSCCO leads to a vortex lattice which should become increasingly two dimensional at high fields and high temperatures. In recent theoretical [14] and experimental [15] work, the layered structure is modeled as coupled superconducting sheets. The dimensional crossover B_{2D} is estimated [14] to be $B_{2D}\sim 4\phi_0/\Gamma d^2$, where d is the interplane spacing and Γ is the effective-mass anisotropy. Estimates [16] for $\gamma=\Gamma^{1/2}$ range from 60 to 200, which together with $d=1.5$ nm gives B_{2D} ranging from 1.0 to 0.1 T. Our observation of the collapse of the critical region at a finite field between 1 and 2 T is tantalizingly close to this prediction.

At all fields, the vortex lattice will become effectively three dimensional at sufficiently low temperatures due to the finite interplane coupling. In two dimensions, the vortex-glass phase transition occurs strictly at $T=0$, in contrast to our data in which the phase transition appears to be at a finite temperature for all fields. The two-dimensional critical behavior is also expected to be dramatically different from the three-dimensional exponents we find. Therefore, we conclude that our observations are related to the three-dimensional vortex-glass transition. However, the exact nature of the dimensional crossover in this system will require further study.

In conclusion we have measured I-V curves in clean BSCCO crystals with picovolt resolution in fields up to 6 T. We find clear evidence for a crossover from a high-temperature, approximately Arrhenius regime to the low-temperature critical behavior of the three-dimensional vortex-glass phase transition. We find critical exponents $\nu(z-1)=7\pm1$ for the vortex-glass transition in good agreement with values previously seen in YBCO single crystals. At fields below 2 T we find the vortex-glass critical region becoming vanishingly small suggesting that the transition might become first order in that region.

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