Observation of a Universal Low Temperature Limit of the Free Flux Flow Resistivity in Superclean Bi$_2$Sr$_2$CaCu$_2$O$_8$ Whiskers

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We report peculiar vortex motion in clean Bi$_2$Sr$_2$CaCu$_2$O$_8$ single crystals, which reveals nearly linear-\(T\) resistivity tails extending to low temperatures. The resistivity was found to satisfy the classical Bardeen-Stephen model for free flux flow, which is otherwise hard to observe under normal experimental conditions in high-\(T_c\) cuprates. Moreover, in the superclean regime, a universal temperature-independent value for the flux flow resistivity was observed, \(\rho_f = 1.4(B - B^*)\). We interpret this carrier-relaxation independent behavior as being related to the dissipation caused by the minigap states within the vortex core. The results are in agreement with theoretical calculations (N. B. Kopnin and G. E. Volovik, Phys. Rev. Lett. 79, 1377 (1997)).

Free flux flow of vortices in the mixed state of superconductors describes the motion of vortices under the influence of Lorentz force and an effective viscosity. The vortices move perpendicular to the applied current and induce an EMF in the current direction. This leads to a sizable magneto-resistance and a very small Hall effect. The classical Bardeen-Stephen (BS) theory describes this phenomenon in terms of the normal-state resistivity and normal electrons in the vortex core. Caroli, de Gennes, and Matricon realized that quantized states of a vortex solid at low temperatures have a universal value independent of the normal-state relaxation time. Nodes in the superconducting gap result in resonance absorption of zero frequency vortex modes. An approach to a Hall angle of \(\pi/2\) has been observed in a 60 K YBCO single crystal. In this work we report the possible observation of the resistivity limit in very clean single crystalline whiskers of Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi-2212) high-\(T_c\) superconductors.

In order to observe free flux flow, one must have samples with very low concentration of pinning centers. In high-\(T_c\) superconductors, this condition is difficult to obtain due to the microscopic layered structure, the small coherence length, and the different order parameter. Because of this, free flux flow has been observed only in narrow ranges of field and temperature or for pulsed large current density. In general, thermally activated flux flow (TAFF) is observed, followed by the formation of a vortex solid at low temperatures. In this paper we report the properties of two Bi-2212 whiskers, both showing free flux flow but with different field dependencies. The differences in magnetoresistance can be correlated with the moderately clean and superclean regimes reached. In the superclean regime, we observed at low temperatures the universal flux flow resistivity which is independent of carrier relaxation.

The whiskers were grown by long-time annealing at temperatures between 835 and 855°C from ceramic (and non-stoichiometric) pellets of BiSrCaCu oxide as described previously. The first whisker (Whisker 1) described here was from a pellet grown at atmospheric pressure (20% O$_2$), and can be assumed to be overdoped. The resistive \(T_c\) is 74.6 K. The second whisker (Whisker 2) was also initially grown at atmospheric pressure. It was then annealed in flowing nitrogen at 500° for 4 hours. This whisker is underdoped with a resistive \(T_c\) of 73.2 K, a pseudogap behavior near 220 K was observed in the normal-state resistivity. The geometry of the whiskers and the attached electrical leads were measured by a scanning electron microscope. The dimensions are as follows (length measured between leads were measured by a scanning electron microscope.

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Resistance measurement was done by the standard four-probe method. Electrical leads were fabricated by sputtering silver stripes onto the whisker followed by attaching copper wires with indium. We used true dc current rather than ac modulation in order to minimize disturbance to the flux flow. Each measurement was done by driving the current in both directions for a few times and averaging the voltages so as to reduce the thermal noise. The current is always along the a-axis and fixed at 0.5 \(\mu\)A (current density \(\sim\) 10 A/cm$^2$), whereas the...
magnetic field was applied along all the three axes and changed between 0 and 5.5 T. One notices that the sample thickness is of the order or smaller than the penetration depth (2600 to 3000 Å in Bi-2212). Because of this, and the large demagnetization effect in the $H \parallel c$ configuration, we assume that the applied field $H$ equals the magnetic induction $B$ in the whiskers.

Figures 1 and 2 show the resistivities for both whiskers in different fields up to 5.5 T. Whisker 2 was only measured in fields of 3, 4, and 5.5 T. We can see that an extended region, where $\rho(T, B)$ is linear in $T$, appears below the extensive fluctuation range near $T_c$ and extends to very low values of $\rho(T, B)$. No sign of TAF II or flux line melting was observed in either whisker. Flux line melting occurs only in fields of 400 G or below and for $T \gtrsim 40$ K, so it is not surprising that we did not observe it. We interpret the vortex motion associated with the long linear $\rho - T$ tails as being in the free flux flow regime. The characteristics of the $\rho(T, B)$ for both whiskers in this regime show certain similarities, as well as differences.

The free flux flow regime starts at a characteristic low temperature for a constant field. We call this field $B^*(T)$, below which the resistance is zero due to immobilization of the vortices. The temperature dependence of $B^*$ could be fitted to:

$$B^* = B_0^*(1 - T/T_c)^n.$$  \hfill (1)

For Whisker 1, we found $n = 3.33\pm 0.05$ and $B_0^* = 24.45$ T. For Whisker 2, the same fitting with fixed $n = 3.33$ yielded a much smaller $B_0^* = 6.71$ T, although the exponent is less certain here due to the fewer fields used ($n = 3.3 \pm 0.3$). All the applied fields are well above the vortex melting line. The fields $B^*(T)$ are close to the depinning line, which is dependent on the amount of disorder in the samples \[2] . In spite of the very similar zero-field transition temperatures, we see that the two whiskers exhibit different properties. In particular, Whisker 2 shows magnetoresistance down to very low temperatures, close to 0 K! If the fitting of eq. (1) can be extrapolated, one would expect non-zero flux flow resistance at 0 K in this whisker at $H = 6.7$ T. Extension of the free flux flow regime to such low temperatures has not previously been observed.

A second difference between the two whiskers is the field dependence of the magnetoresistivity. For Whisker 1, $\rho_f/\rho_n$ is linear in fields higher than about 1.5 T and in the temperature range from 40 to 60 K. At lower fields, a curvature appears in $\rho_f$ due to the 3D to 2D crossover. We use then the Bardeen-Stephen model \[2] in its differential form in the high-field regime:

$$\frac{d\rho_f/\rho_n}{dB} = \frac{1}{B_{c2}}.$$  \hfill (2)

This corresponds to the field region for pancake vortices with small interplane interaction. For $H \gtrsim 1.5$ T, we obtained reasonable $B_{c2}$ values both for $H \parallel c$ (in the range of 40 to 60K ) and $H \parallel b$ (65 to 70 K). As expected, the fields extrapolate to $T_c$ with slopes of -1.33 T/K ($H \parallel c$) and -30.8 T/K ($H \parallel b$), as shown in Fig. 3. These data are in good agreement with literature values both for the temperature dependence and the anisotropy \[3]\.

In the case of Whisker 2 no such analysis is possible. We show in Fig. 4 both $\rho_f$ and $\rho_f/\rho_n$ as a function of field for this whisker. As can be seen, $\rho_f/\rho_n$ at high temperatures are only weakly dependent on field above 3 T. At lower temperatures, the dependence of the flux flow resistivity $\rho_f$ on field increases, and assumes below approximately 30 K a uniform, temperature independent slope of $d\rho_f/dT = 1.40 \mu\Omega cm/T$. Attempts to fit to the Bardeen-Stephen expression of eq. (2) would lead to unacceptable values of $B_{c2}$ and wrong temperature dependence.

The characteristic behavior of $\rho_f$ in Whisker 2 is the near-linearity of $\rho_f$ for fields above 3 T. Below 3 T we have extrapolated $\rho_f$ at each temperature to $B^*$ calculated from eq. (1). This involves curvature which probably again is connected to the 3 D to 2 D crossover at high fields. At temperatures below about 30 K, $\rho_f(B)$ has the same slope, and extends to $B^*$ for $T \lesssim 15$ K. In this regime we have, therefore:

$$\rho_f(T) = \rho_0(B - B^*),$$  \hfill (3)

where the constant is given by $\rho_0 = 1.40 \pm 0.1 \mu\Omega cm/T$. Above $T \sim 30$ K, the slope decreases and reaches 0.58 $\mu\Omega cm/T$ at 55 K, or one third of the low-temperature limiting value.

The different magnetoresistive behavior of the two whiskers is related to their microscopic properties. We first discuss their normal-state properties. For Whisker 1, a linear temperature dependence of $\rho_n$ (in zero field) was obtained down to the fluctuation regime near $T_c$. We base our analysis on an extrapolation of this linear part to the lowest temperatures. The axis intercept at 0 K is about 23.0 $\mu\Omega cm$, or about 6.4% of the resistivity at 300 K. The two-dimensional square resistance $R_{\square}$ per CuO$_2$ layer is $R_{\square} = \rho_n/d$ with $d = 15$ Å for Bi-2212. $R_{\square}$ varies between 2390 $\Omega$ at 300 K to 190 $\Omega$ at 5 K. From this we calculate the product $k_F l = h/e^2 R_{\square}$, where $k_F$ is the radius of Fermi surface and $l$ the mean free path. $k_F l$ obtained in this way varies between 10.8 at 300 K and 135 at 5K. At low temperatures, Whisker 1 is therefore in the moderately clean regime. One can estimate $l$ from this by using a reasonable value for $k_F$ ($\approx 0.33$ Å$^{-1}$), $l$ then reaches a value of 330 Å at 5 K. For Whisker 2, the linear part of $\rho_n$ extrapolates to a nearly zero $\rho(0 K)$ ($\pm 5 \mu\Omega cm$). $R_{\square}$ in this case changes from 3400 $\Omega$ (at 300 K) to 56.7 $\Omega$ (at 5 K), and accordingly, $k_F l$ varies from 7.6 to 456. This leads to an estimate for $l$ ($k_F = 0.33$ Å$^{-1}$) of 1110 Å at 5 K. Therefore, Whisker 2 enters further into the clean or superclean regime at low temperatures,
although this occurs only below 30 K. It is, however, important to notice that in the field of 5.5 T, we can explore further into the superclean regime with Whisker 2. A more drastic difference between the two whiskers is evident in the minigap (ω) of the quasiparticle states within the vortex core \( \frac{\Delta_0^2}{\varepsilon_F} \). The minigap is given by:

\[
\omega_0 = \frac{\Delta_0^2}{\varepsilon_F} \tag{4}
\]

where \( \Delta_0 \) is the (maximum) superconducting gap at 0 K, and \( \varepsilon_F \) the Fermi energy. We use \( \varepsilon_F = 500 \) meV for both whiskers \[15\]. The value of \( \Delta_0 \) is, however, drastically different. For Whisker 1 (overdoped), we estimate \( \Delta_0 = 10 \) meV, and for Whisker 2 (underdoped) \( \Delta_0 = 25 \) meV \[16\]. The minigaps are then 0.20 meV for Whisker 1, and 1.25 meV for Whisker 2. The region of superclean behavior is governed by the size of the product \( \Gamma = \omega_0 \tau \), where \( \tau \) is the normal-state relaxation time. The approximately six-fold increase of \( \omega_0 \) for Whisker 2 over that of Whisker 1 is remarkable. We can further estimate \( \tau \) from

\[
\tau = \frac{4\pi\lambda_0^2}{c^2\rho_n} \tag{5}
\]

where \( \lambda_0 \) is the penetration depth at 0 K. We use \( \lambda_0 = 2600 \) Å for Whisker 1 \[16\], and a slightly larger \( \lambda_0 = 3000 \) Å for Whisker 2 \[17\]. For Whisker 1, the relaxation time obtained from eq. (5) reaches 0.37 psec at the lowest temperatures, and \( \Gamma = \omega_0 \tau = 0.1 \). For Whisker 2, on the other hand, \( \tau = 6.64/T \) (psec), so that \( \tau \) reaches very large values at low temperatures (2.54 psec for \( T = 5 \) K). It appears, therefore, that in this whisker, the superclean region is reached at low temperatures. All the estimates are based on the extrapolated normal-state resistivity, without adjustment for a possible reduction of \( \rho_n \) in the vortex cores. The parameter \( \Gamma \) is, therefore, at low temperatures considerably larger for Whisker 2 than for Whisker 1. This is due to the combination of a larger \( \omega_0 \) and a smaller \( \rho_n \) for Whisker 2. Estimates of \( \Gamma \) and \( k_Fl \) are shown in Fig. 5.

In the moderately clean regime, the free flux flow ohmic resistivity is given by Kopnin and Volovik \[1\] as:

\[
\rho_f = \frac{B}{n_e\varepsilon F \ln(T_c/T)} \tag{6}
\]

In the superclean regime the free flux flow resistivity assumes a universal non-zero limit, independent of the relaxation time (and hence normal-state resistivity), which is given by:

\[
\rho_f = \frac{\pi B}{2n_e\varepsilon F} \tag{7}
\]

The temperature at which the moderately clean value of \( \rho_f \) equals the low temperature ideal limit was estimated by using the above value of \( \Gamma \) for Whisker 2, and is found to be \( T = 23 \) K. This is in good agreement with our observations.

Since in Whisker 2 at low temperatures, the free flux flow sets in at \( B^* \) and is linear in \( B \), we use eq. (7) in a modified form

\[
\rho_f = \frac{\pi(B - B^*)}{2n_e\varepsilon F} \tag{8}
\]

The only system parameter here is \( n_h \), which can be estimated from the zero-temperature penetration depth \( \lambda_0 = 3000 \) Å as \( n_h = 0.63 \times 10^{21} \) cm\(^{-3} \). We would then expect from eq. (8) a limiting free flux flow resistivity of \( 1.56(B - B^*) \mu\Omega \text{cm} \). This compares extremely well with the observed value of \( 1.4(B - B^*) \mu\Omega \text{cm} \). The observed limiting resistivity thus most likely represents the predicted universal behavior. This result is connected to the gap nodes in a \( d \)-wave superconductor, which results in higher order nodes in the minigap \[3\].

There have been several observations of free flux flow in moderately clean or superclean high-\( T_c \) superconductors by Matsuda et al. \[18\], Harris et al. \[19\], and Doettinger et al. \[20\]. Harris et al. studied the magnetoresistance in an oxygen deficient single crystal of YBCO with \( T_c = 64 \) K in fields up to 24 T. They find that the normally small Hall angle increases with falling temperatures and reaches \( 70^\circ \) at 13 K. This increase is due to the expected deviation of vortex motion from perpendicular to the current towards the current direction with increasingly clean conditions characterized by \( \omega_0 \tau \). The same effect leads to the reduction in the ohmic component of the flux flow resistance. The ohmic resistivities of Ref. 5 are indeed very similar to those seen from Whisker 2. At temperatures below about 30 K and in fields above 10 T, they observed a slope \( d\rho_f/dB \) of 2.4 \( \mu\Omega \text{cm} \)/T. This is similar to what we found, but larger than the theoretical value of 1.42 \( \mu\Omega \text{cm} \)/T from eq. (8) \( n_h \) is estimated from \( \lambda_0 = 2500 \) Å \[20\] for oxygen-deficient YBCO. The linear dependence of the Hall angle on \( \omega_0 \tau \) observed by them suggests that the universal limit is not quite reached in their sample.

In conclusion, we observed free flux flow behavior at low temperatures in the magnetoresistance of Bi-2212 whiskers. For an underdoped sample, we observed free flux flow down to 5.4 K in a field of 5.5 T. Below about 30 K, the free flux flow resistivity assumes a universal, temperature-independent value, in numerical agreement with the calculations of Kopnin and Volovik \[1\].

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Figure Captions
Fig. 1. The resistivity of Whisker 1 in fields between 0 and 5.5 T. Solid curves: $H \parallel c$; dotted curves: $H \parallel b$.
Fig. 2 The resistivity in 3, 4 and 5.5 T of Whisker 2. Fits to the linear-$T$ regime are shown.
Fig. 3 Estimates of $B_{c2}$ for Whisker 1 obtained from the Bardeen-Stephen Theory, eq. (2).
Fig. 4 The resistivity in the free flux region of Whisker 2. (a) Resistivity $\rho_f$; (b) Reduced resistivity $\rho_f/\rho_n$, where $\rho_n$ is the extrapolated normal-state resistivity. The dotted lines are rough extrapolations to the onset field from eq. (1).
Fig. 5 Estimates of $k_Fl$ and $\Gamma = \omega_0\tau$ for Whiskers 1 and 2. The regimes over which we observed free flux flow are shown by the heavy segments.
