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Thermally Activated Dissipation in $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$

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A new dissipation behavior is reported in superconducting $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ for all temperatures below T_c and all magnetic fields exceeding H_{c1}. The current-independent electrical resistivity is thermally activated and can be described by an Arrhenius law with a single prefactor and a magnetic-field- and orientation-dependent activation energy $U_0(H,\phi)$. This behavior is markedly different from past observations and will be discussed in terms of flux creep and flux flow. This thermally activated behavior implies a finite resistance at all temperatures and all fields exceeding H_{c1} determined by the activation energy as the only parameter.

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One of the most prominent features of type-II superconductors is their ability to carry large transport currents in the presence of a magnetic field. The limiting value, the critical current density, is given by the balance of two opposing forces acting on the magnetic flux lines: The pinning force due to spatial variations of the condensation energy and the Lorentz force exerted by the transport current.[1] Energy is dissipated whenever flux lines move. Traditionally, one distinguishes two regimes of dissipation: "flux creep" when the pinning force dominates[2] and "flux flow" when the Lorentz force dominates.[3,4] Extensive studies in the past revealed the distinct characteristics for both regimes.[5-8]

Here we report on the dissipation behavior in the mixed state of single-crystal $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$. We found a current-independent resistance which is thermally activated and can be described by an Arrhenius law, $\rho=\rho_0\exp(-U_0/T)$. The activation energy U_0 depends weakly on magnetic field and orientation and is relatively small. The prefactor in the Arrhenius law ρ_0 is magnetic field and orientation independent and is 3 orders of magnitude larger than the normal-state resistance. This behavior is distinctly different from previous observations in traditional superconductors.[8] The present results are discussed in terms of flux creep and flux flow models, from which we can estimate several microscopic parameters. The relatively small value for the activation energy compared to the transition temperature T_c, in combination with a large pre-exponential factor ρ_0, makes this dissipation behavior observable by conventional techniques.

The high-quality single crystal was grown from an alkali-chloride flux, as described by Schneemeyer *et al.*[9] Extensive characterization of these crystals has been described elsewhere.[9] An optically flat piece was obtained by cleaving the crystal along the a and b axis to a rectangle of 1.0×0.22 mm^2. Four low-resistance Ag contacts were sputtered on the crystal in a bar-shaped geometry. The distance between the voltage contacts is 0.37 mm. With estimation of the thickness of the crystal d as $d\approx1$ μm, the room-temperature resistivity is 140 $\mu\Omega$ cm. The temperature was measured with a carbon-glass resistor and accurate corrections for its magnetoresistance were applied. A magnetic field up to 12 T could be applied perpendicular and parallel to the basal plane but

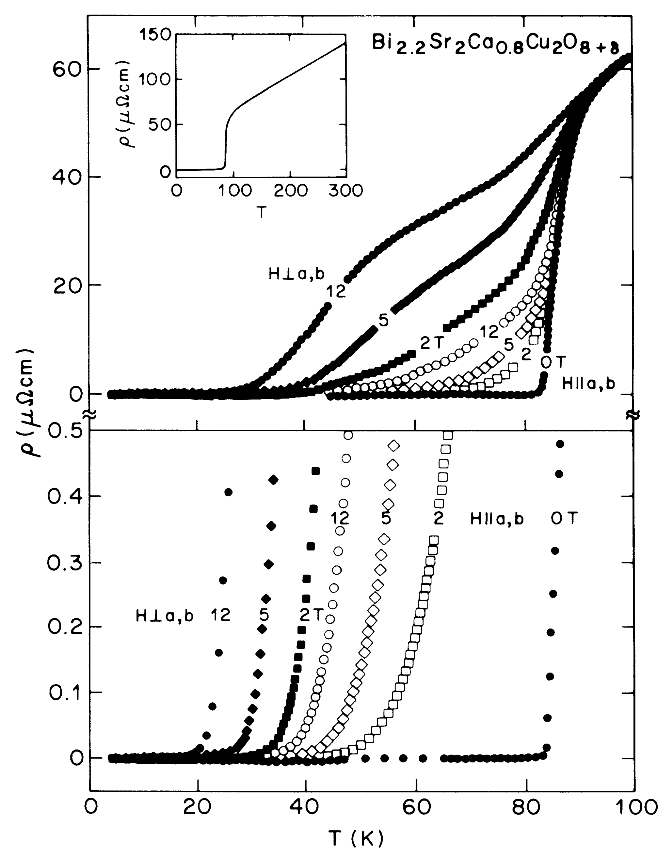

FIG. 1. Temperature dependence of the electrical resistivity of $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ in three selected magnetic fields, 2, 5, and 12 T, oriented parallel (open symbols) and perpendicular (filled symbols) to the basal plane. The lower part of the figure is a magnification by about a factor of 100 to emphasize the exponential behavior. Inset: the zero-field resistivity up to room temperature.

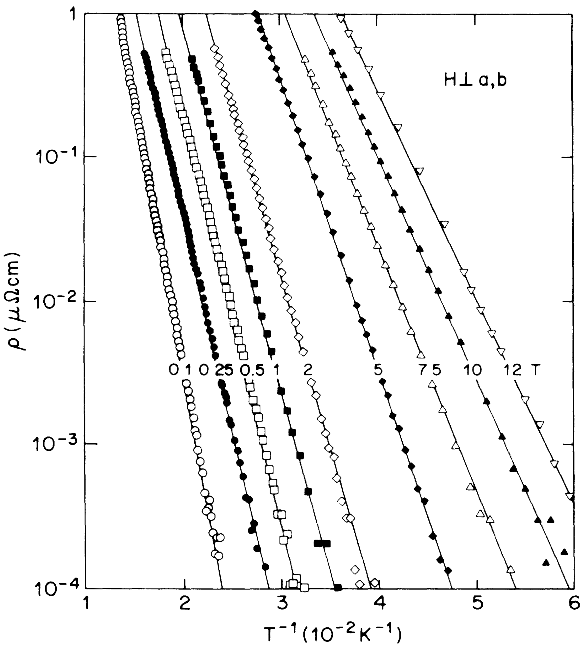

FIG. 2. Arrhenius plot of the electrical resistivity of $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ for all measured magnetic fields perpendicular to the basal plane ranging from 0.1 to 12 T. All lines have common intercept for $T^{-1}=0$ at $\rho \simeq 10^5$ $\mu\Omega$ cm. The activation energy U_0 is given by the slopes.

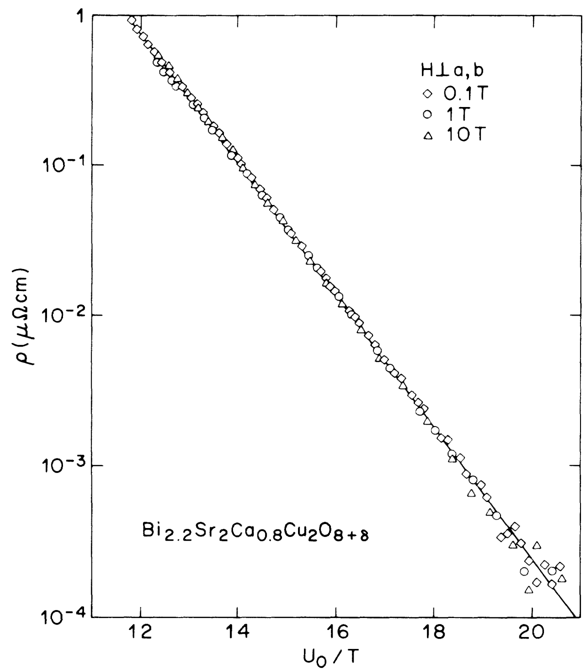

FIG. 3. Universal behavior of the thermally activated electrical resistivity for the data of Fig. 2 by use of a normalized temperature scale U_0/T.

always perpendicular to the current direction.

In the upper part of Fig. 1 we show the temperature dependence of the electrical resistivity $\rho(T)$ for zero field and three fields parallel and perpendicular to the basal (a,b) plane using a dc current of 0.1 mA. In a previous paper[10] we concentrated on the $\rho(T)$ behavior in the vicinity of T_c, from which we determined the values of dH_{c2}/dT. In combination with magnetization measurements of H_{c1}, we estimated various thermodynamic parameters. This figure also clearly shows the large magnetoresistance down to relatively low temperatures. Still, this behavior does not exhibit the "onset" of the resistivity, which appears to happen at yet lower resistivities.

In this Letter we concentrate on the resistivity range between $\sim(10^{-6}\text{-}10^{-2})\rho_N$. These measurements are shown in more detail in the lower part of Fig. 1. We checked the linearity of the I-V curves for currents between 0.1 and 100 mA, and temperatures between 10 and 80 K in a field of 1 T. We found that deviations from linearity start above 30 mA. We therefore chose a measuring current well below this value at 10 mA. The curves in the lower part of Fig. 1 show the apparent "onset" of resistivity for magnetic fields both parallel and perpendicular to the basal plane.

In Fig. 2 we replot these data for $H_{\perp a,b}$ as $\log\rho$ vs T^{-1}, and show additional data for other magnetic fields. From this plot the thermally activated behavior of the resistance is immediately apparent. The slope of the curves is the activation energy $U_0(H,\phi)$. A similar set of curves was obtained for $H_{\parallel a,b}$. Similar results were obtained on a different sample, studied in less detail.

In Fig. 3 we examine the magnetic field dependence of the $H_\perp$ curves more closely. Plotting $\log\rho$ versus a normalized temperature scale U_0/T, we obtain one generic straight line for the resistance. Of particular importance is that the $H_\parallel$ measurements also fall exactly on this line. Thus the resistivity for all field magnitudes and directions can be described with a single prefactor as all curves have a common intercept in the limit $T^{-1}\rightarrow 0$, independent of magnetic field and orientation. The value of this prefactor, obtained by extrapolation over 5 orders of magnitude, is $(1.3\pm0.5)\times10^5$ $\mu\Omega$ cm corresponding to a resistance of 2000 ± 750 Ω or a sheet resistance of about $10^3\Omega$/sq. In comparison, the room-temperature resistivity of about 140 $\mu\Omega$ cm or 2.1 Ω is 3 orders of magnitude smaller.

Thus we can represent the data by one universal function:

$$\rho(T,H,\phi)=\rho_0\exp[-U_0(H,\phi)/T],$$

with one single $\rho_0\simeq 0.1$ Ω cm for all magnetic fields and orientations. In Fig. 4 we show the magnetic field dependence of the activation energy, U_0, for $H_\parallel$ and $H_\perp$. First, we note that the activation energies are relatively low with values between 300 and 3000 K. This, combined with the large values of T_c and ρ_0, is of course the

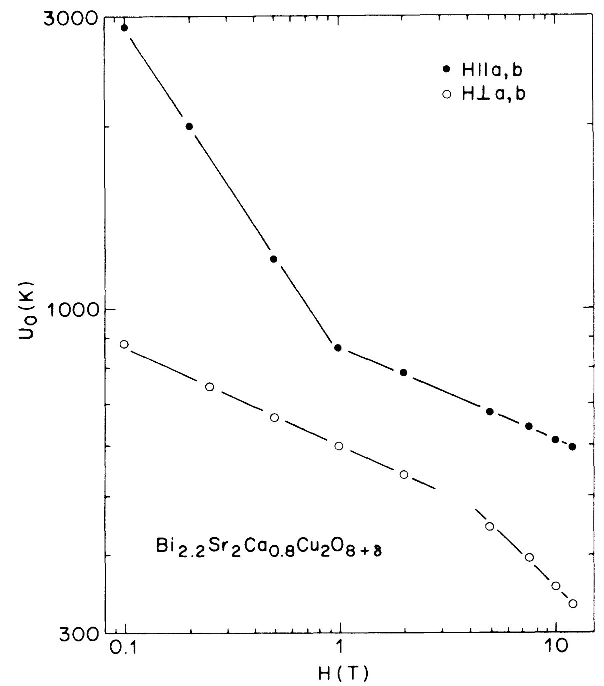

FIG. 4. Magnetic field dependence of the activation energy U_0 of $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ in two orientations. The linear portions of the data suggest power laws $U_0 \sim H^{-\alpha}$ with $\alpha \simeq \frac{1}{2}$ and $\frac{1}{6}$ for $H_\parallel$ and $\alpha \simeq \frac{1}{6}$ and $\frac{1}{3}$ for $H_\perp$.

reason why this behavior is so easily observable. Second, the anisotropy in U_0 is only moderate and ranges from 1.5 to 3. Finally, we note that Fig. 4 suggests a power-law dependence of $U_0(H) \sim H^{-\alpha}$, with various exponents α. For $H_\parallel$ below 1 T we find $\alpha = 0.48 \pm 0.04 \simeq \frac{1}{2}$, or U_0 is proportional to the flux line spacing. For $H_\parallel > 1$ T, we find $\alpha = 0.15 \pm 0.02 \simeq \frac{1}{6}$, and for $H_\perp < 3$ T, $\alpha = 0.16 \pm 0.02 \simeq \frac{1}{6}$. For $H_\perp > 3$ T, the power is $\alpha = 0.33 \pm 0.05 \simeq \frac{1}{3}$. The power-law behavior, the value of the power, and the nature of this transition might, though unexplained, be of particular importance to a theoretical description of the observed behavior.

We now consider several aspects in more detail. Remarkably, for given field strength and orientation the data can be described by a temperature-independent activation energy. Within the framework of "flux creep" one might anticipate a distribution of energies due to various possible pinning strengths. Furthermore, a description of the dissipation in terms of flux motion would imply a temperature dependence of the activation energy, due to the temperature dependence of the condensation energy and coherent lengths. Our data, however, are accurately described by one temperature-independent activation energy.

Even more remarkable is the observation of a single prefactor ρ_0 that is independent of temperature, magnetic field, and orientation. This prefactors seems unrelated to the normal-state resistivity as it is 3 orders of magnitude larger. It is unclear to what extent this prefactor is different from sample to sample or for various materials.

The central question raised by the present results concerns the nature of the dissipation mechanism. In the following we will discuss the present results in terms of flux creep,[2] although alternative processes have been proposed in the past for thermally activated dissipation.[4,8,11-15] In a flux-creep model the creep velocity v_ϕ is given by

$$v_\phi = 2 v_0 L \exp(-U_0/k_B T) \sinh(JBV_c L/k_B T),$$

with v_0 the attempt frequency of a flux bundle of volume V_c to hop over an energy barrier U_0 and move a distance L. J is the current density and B the magnetic induction. The linearity of the I-V curves (or J-v_ϕ) sets an upper limit to $V_c L$. Assuming a hopping distance $L = a_0$, i.e., the vortex separation, we find that V_c is not larger than the volume of one vortex, $a_0^2 d$. Using then the approximation $V_c L \approx a_0^3 d$ and linearizing the hyperbolic sine, we find that the attempt frequency is

$$v_0 \approx \rho k_B T / 2\phi_0^2 d \exp(-U_0/k_B T) \approx 10^{11}\ \text{Hz}.$$

This is a large frequency compared to estimates for conventional superconductors between 10^5 and 10^{11} Hz. Clearly, this simplified model cannot account for all observations, such as the isotropic value of ρ_0 which suggests an isotropic value for V_c, and a more detailed description is required. We emphasize that in this flux-creep model the pinning force always exceeds the Lorentz force.

At higher temperature the exponential increase of the resistivity will saturate and is probably limited by the viscosity of the vortex system. This would result in a resistivity as given by the Stephen-Bardeen model.[7]

Our measurements confirm the lack of threshold behavior in the I-V characteristics, reported by van Dover *et al.*[14] Further, the dissipation mechanism described here can serve as a characterization of different samples and materials as the electrical transport properties are completely determined by two parameters, the activation energy U_0 and the prefactor ρ_0. Future work will therefore examine the influence on the activation energy of various treatments such as irradiation, heat treatment, etc.

Further studies will investigate to what extent the present observations are generic to all high-T_c superconductors. We find evidence that a similar dissipation mechanism might indeed be operative in high-T_c superconductors from measurements[16,17] of the time dependence of the magnetization of single-crystal $Ba_2YCu_3O_7$. The magnetic relaxation observed in these measurements was also interpreted in terms of thermally activated flux creep.

In conclusion, we have found a new dissipation behavior in the mixed state of single-crystal $Bi_{2.2}Sr_2Ca_{0.8}$-

$Cu_2O_{8+\delta}$. The dissipation process is current independent, thermally activated, and can be described with an Arrhenius law with a single prefactor and a magnetic-field- and orientation-dependent activation energy $U_0(H, \phi)$. The activation energy is relatively small and weakly dependent on magnetic field and orientation. This dissipation mechanism is discussed in terms of flux creep and flux flow models and gives new insights into the dissipation mechanisms in the mixed state of high-T_c superconductors.

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