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Observation of the Kosterlitz-Thouless transition and of vortex fluctuations in superconducting single crystals of Bi-based cuprates

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We have observed power-law behavior in the current-voltage characteristics of single crystals of $Bi_2Sr_2Ca_1Cu_2O_{8+y}$ and $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ both in zero and in applied magnetic fields. The observed power-law behavior, $V \propto I^{\alpha(T)}$ near the transition with a characteristic Nelson-Kosterlitz jump in the exponent $\alpha(T)$ at $T=T_c$ gives evidence for a Kosterlitz-Thouless (KT) transition in wihch vortex-antivortex pairs are dissociated within the superconducting planes. In a magnetic field, the KT transition is suppressed because field-induced vortices induce dissipation and reduce the stability of vortex-antivortex pairs. The interaction of vortex pairs with interlayer flux lines has been discussed.

The transport properties of high-T_c superconductors have several interesting and important features. Among them, the transport dimensionality and the non-ohmic behavior observed near the superconducting transition temperature need to be explained clearly. It is well known that the high-T_c superconductors have two-dimensional (2D) properties due to the layered structure of the CuO_2 superconducting planes which interact weakly with each other. Kosterlitz-Thouless (KT) (Ref. 1) behavior has therefore been expected, and the onset of a resistive state in several high-T_c materials is described[2-5] in terms of a KT transition. The power law of the current-voltage (I-V) characteristics ($V \propto I^{\alpha(T)}$) is described in the framework of the KT model near to the mean-field critical temperature T_{c0}.

In the KT model of a 2D system the phase transition at a critical temperature $T_{\rm KT}$ is determined by the dissociation of vortex-antivortex pairs (pancake vortices) which interact mutually with a logarithmic potential $U(r)=2\pi K k_B T \ln(r/\xi)$, where ξ is the Ginzburg-Landau (GL) coherence length, and $\pi K=\phi^2 d/16\pi^2 k_B T\lambda^2$ the stiffness constant of the KT theory. d is the thickness of the fluctuating superconducting sheet and λ is the penetration depth in the ab plane. When $T_{\rm KT}<T_{c0}$, the pairs can be broken by an applied current density causing dissipation and a non-ohmic behavior as the temperature is increased. This gives a sudden jump in the exponent $\alpha(T)=1+\pi K$ from 3 to 1 at a temperature $T_{\rm KT}$ which gives the 2D nature of the superconductors. The observed power law in the I-V characteristics, suggesting a scaling law, cannot be derived from the standard flux-flow or flux-creep phenomena. The most important characteristic feature of the direct evidence of KT transition is the universal Nelson-Kosterlitz jump[6] in the power-law exponent as a function of temperature.

In this paper, we report the observation of the Nelson-Kosterlitz jump in α in zero magnetic field and also the behavior of the exponent α in external applied magnetic fields in single crystals of $Bi_2Sr_2Ca_1Cu_2O_{8+Y}$ (BSCCO) and $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ (BPSCCO). We show how an external field plays a crucial role in the dynamics of the KT transition.

The BSCCO and BPSCCO crystals used in our studies were grown by a self-flux method. The details of the growth process have been discussed elsewhere.[7] Chemical analysis was performed by EPMA. Typically, we used single-crystal samples of $1.3\times1.0\times0.1$ mm^3 with four evaporated Ag contacts. Silver leads were attached with silver epoxy and heated for 1 h in air at about 250 °C. The contact resistance was comparable to the sample resistance at room temperature. Measurements of the I-V characteristics were carried out at a fixed temperature in various magnetic fields in a continuous flow cryostat within a 17-T superconducting magnet. In our measurements, the absolute temperature in zero magnetic field was determined with a Rh-Fe thermometer. During a field sweep, the temperature was controlled using a magnetic field-independent capacitance sensor with a temperature accuracy better than 0.01 K. The sample was mounted with a magnetic field parallel to the ab plane and the current was sent within the ab plane either parallel or perpendicular to the applied magnetic field. Measurements were taken with both polarities of current and the average was taken. The maximum current corresponding to 100 A/cm^2 was sent with a current pulse less than 0.5 sec. dc voltages were measured to an accuracy less than 10 nV.

In Figs. 1 and 2 we show the I-V characteristics of BSCCO and BPSCCO crystals at various temperatures in zero field. The experimental data points plotted in the $\log_{10}I$-$\log_{10}V$ plots form quite good straight lines (shown as solid lines) in all temperature and magnetic-field regions displaying a power law, $V \propto I^{\alpha(T)}$. The nonlinearity arises from a lowering of the vortex-antivortex energy as the current acts on the vortex and the antivortex in opposite directions.[2,7] The exponents derived from the slopes of the I-V curves (log-log plot) do not depend on current density within the ranges used in the experiment. Figures 3 and 4 show the behavior of the exponent, α as a function of temperatures in zero magnetic field for BSCCO

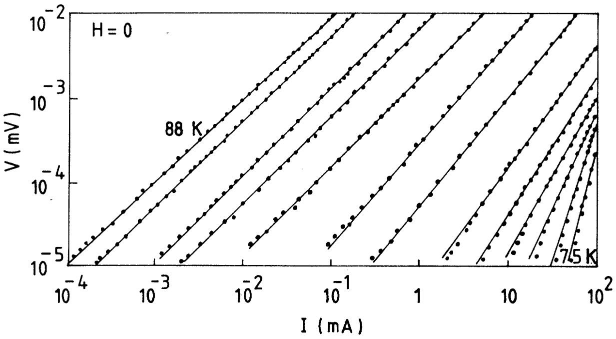

FIG. 1. Plots of $\log_{10}I$-$\log_{10}V$ for temperatures 88, 87.3, 86.3, 85.7, 84.3, 83.3, 82.3, 81.2, 80.2, 79.3, 78, 76.3, and 75 K in zero magnetic field for the BSCCO crystal.

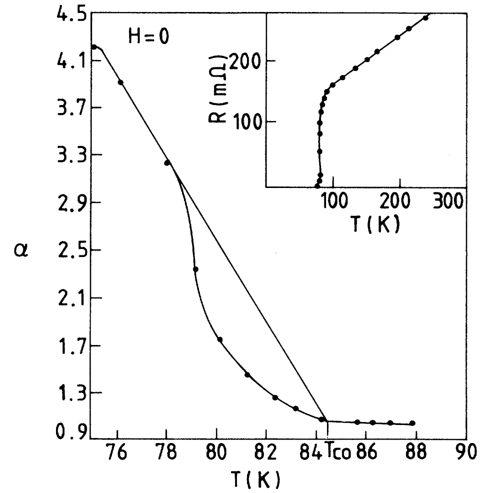

FIG. 3. Temperature dependence of the power-law exponent, α as a function of temperature. The Nelson-Kosterlitz jump is clearly shown. The solid lines are shown from curve fits. Inset: temperature dependence of the resistance up to room temperature for the BSCCO crystal.

and BPSCCO crystals. The insets in Figs. 3 and 4 show the zero-field resistive transition in temperature up to 300 K. The room-temperature resistivity is less in BPSCCO in comparison to BSCCO crystal due to the presence of Pb in the BPSCCO crystal. The corresponding $\alpha(T)$ curve, presented in Figs. 3 and 4, shows an abrupt jump in the power-law exponent from 3 to 1 at the KT transition temperature T_{KT}. The T_{c0} and T_{KT} of the BSCCO crystal were found to be 84.5 and 78.8 K, while those of the BPSCCO crystal were 83.8 and 81.3 K, respectively.

Figures 5 and 6 show the I-V characteristics at various temperatures of the BSCCO and BPSCCO crystals in a magnetic field of 5 T. Similar measurements were taken in magnetic fields of 0.5, 1, 2, and 8 T and all curves show a power-law behavior in all measured temperatures. The power-law exponent α is plotted in Figs. 7 and 8 for BSCCO and BPSCCO crystals, respectively, as a function of field at various temperatures. Both the figures show that α decreases rapidly with increasing field up to about 2 T. The decrease is very slow at higher fields, and the value of α tends to unity in high magnetic fields. Figure 9 shows the temperature dependence of the power-law exponent at various magnetic fields for the BPSCCO crystal. It is noted that T_{KT} is suppressed by the application of magnetic field. The Nelson-Kosterlitz jump as a function of temperature is suppressed in high magnetic fields.

In the framework of the KT model, the formation of topological excitation pairs is studied in a 2D system in

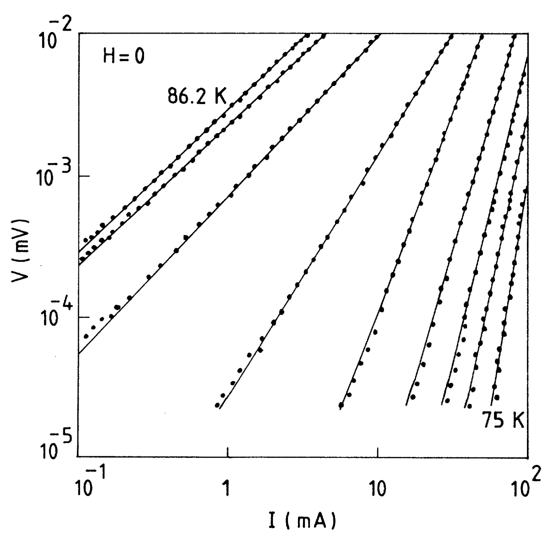

FIG. 2. Plots of $\log_{10}I$-$\log_{10}V$ for temperatures 86.2, 85, 83.37, 82.26, 81.3, 80.3, 79.4, 78.5, and 78 K in zero magnetic field for the BPSCCO crystal.

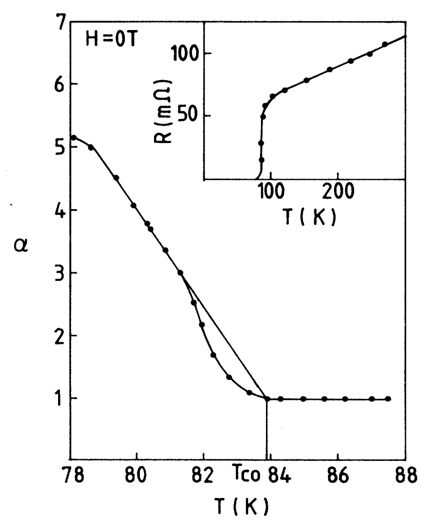

FIG. 4. Temperature dependence of the power-law exponent, α as a function of temperature. The solid lines are shown from curve fits. Inset: variation of resistance with temperature up to room temperature for the BPSCCO crystal.

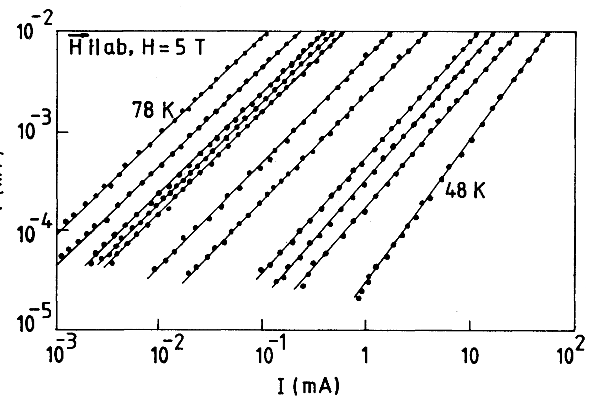

FIG. 5. Plots of $\log_{10}I$-$\log_{10}V$ for temperatures 78, 75.15, 74, 70.1, 68.3, 63.4, 59.6, 53.5, 52.5, 51, and 48 K in 5 T for the BSCCO crystal.

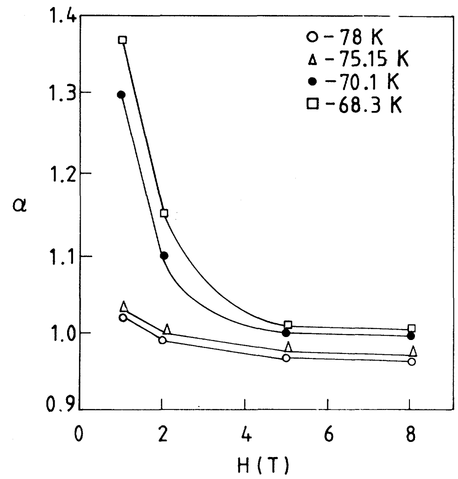

FIG. 7. Magnetic-field dependence of the power-law exponent at various temperatures for the BSCCO crystal. The continuous lines are shown from curve fits. A slight fall in α below 1 at higher temperatures and magnetic fields is due to a small experimental error.

which the interaction potential varies logarithmically with the distance.[1] In superconductors, the topological defects are vortices of opposite helicity. In zero magnetic field such vortex-antivortex pairs are created spontaneously by thermal fluctuations and dissociate at T_{KT}. This dissociation is assisted by electrical currents at lower temperatures. The free vortex pairs produce a resistance to the moving electric charges and dissipation occurs. The observed power law, $V \propto I^{\alpha(T)}$ is the consequence of the dissociation process of the bound vortex-antivortex pairs by the current flow. Pairs present in zero magnetic field, for $T < T_{KT}$, are pulled apart and finally separated by the Lorentz force $J\phi_0/c$ generated by the applied current. The observed power-law behavior in the I-V characteristics results.

If we consider the renormalization group method,[1,6] for $T \geq T_{KT}$ or $T \leq T_{KT}$, the scaling behavior is found to be quite different. It predicts the existence of a topological phase transition between two states, binding and unbinding, of the vortex-antivortex pairs. The theory clearly shows that, for $T \leq T_{KT}$, $\alpha \geq 3$ and for $T \geq T_{KT}$, $\alpha = 1$. The exponent α changes discontinuously at T_{KT} which is well known as the Nelson-Kosterlitz jump. This typical jump for KT transition is clearly seen in Figs. 3 and 4 for the BSCCO and BPSCCO single crystals. The resistance curves given in insets of Figs. 3 and 4, at higher temperatures $R(T)$ can also be well described by the Aslamazov-Larkin theory for the fluctuation contribution to the conductivity of a 2D superconductor.

The application of a magnetic field to the superconductors modifies the KT transition in a different way. In a sufficiently strong magnetic field applied parallel to the *ab* plane we observed a similar power-law behavior (Figs. 5

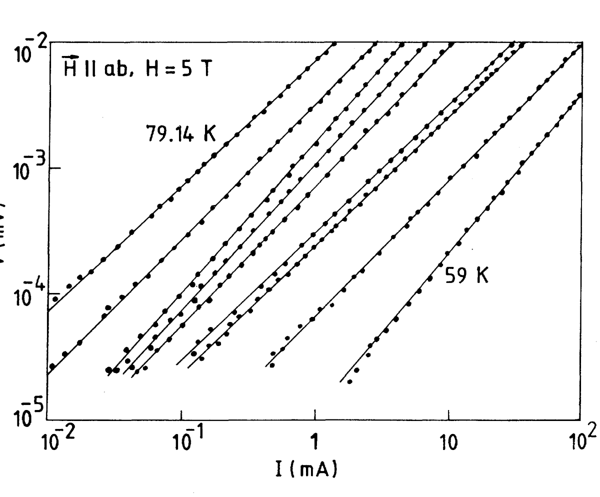

FIG. 6. Plots of $\log_{10}I$-$\log_{10}V$ for temperatures 79.14, 77, 75.8, 74.1, 72, 68.8, 67.1, 63.1, and 59 K in 5 T for the BPSCCO crystal.

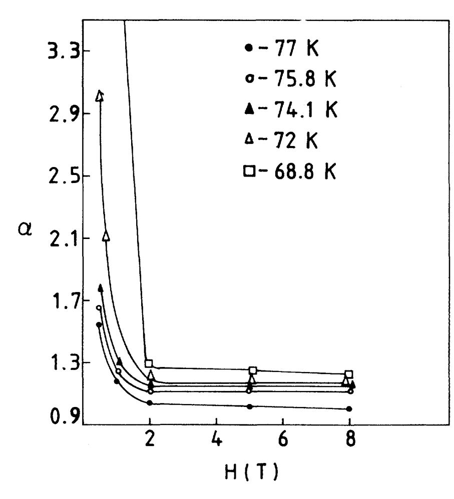

FIG. 8. Magnetic-field dependence of the power-law exponent at various temperatures for the BPSCCO crystal. The solid lines are shown from curve fits.

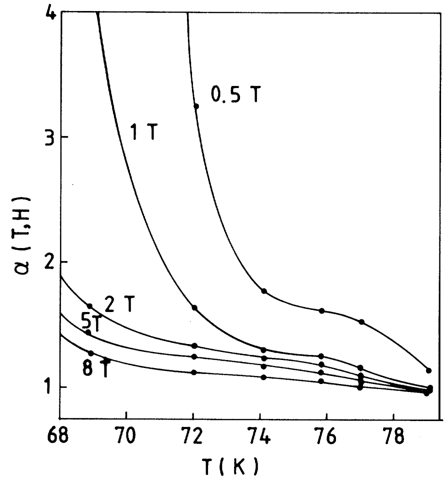

FIG. 9. Temperature dependence of the power-law exponent, $\alpha\,(T,H)$ at various field for the BPSCCO crystal. The solid lines are shown from curve fits.

and 6) to that observed in zero field. However, from Fig. 9, it is clear that T_{KT} is suppressed by the magnetic field. The power-law exponents reveal the remarkable feature of a universal jump in small magnetic fields. The decrease in T_{KT} implies that a magnetic field enhances the dissociation of bound vortex-antivortex pairs. An external magnetic field introduces excess vortices into the system containing vortex-antivortex pairs. The interaction between vortex and antivortex is attractive because of the opposite direction of circulation, while the interaction between vortices of similar circulation is repulsive. These repulsive and attractive forces acting on the pairs from the external vortices can break up the pairs, causing T_{KT} to be suppressed. In our study, basically a magnetic field is applied parallel to the *ab* plane where the magnetic flux is concentrated along the layers. The magnetic flux enhances the dissociation process. In the case of a magnetic-field component perpendicular to the *ab* plane, free 2D vortices are also created and the number of such vortices increases linearly with increasing field. However, Figs. 5 and 6 show that the power-law exponent, which is a measure of the ease of free vortex creation, becomes nearly constant with increasing fields. This predicts that the number of free vortices created by pair breaking is constant in higher fields oriented parallel to the *ab* plane. Any excess dissipation in this field configuration can be explained by the presence of a finite field component perpendicular to the *ab* plane.

There are two cases, (a) $H < H_{c1}$, and (b) $H > H_{c1}$, for which the field dependence of the I-V relation can arise. The formation of energy of a single-point vortex is proportional to $\ln(R_0)$, where R_0 is the linear dimension of the crystal and the formation of a flux line requires a macroscopic energy. For $H < H_{c1}$, the field dependence of the I-V characteristics can arise only from surface effects. The mean field H_{c1}^0 vanishes at T_c and is extremely small at T_{KT}. For a BPSCCO crystal with

$$H_{c1}^0(T) = 150[(T_{c0} - T)/T_{c0}1]G$$

we find $H_{c1} = 4.5$ G with $\Delta T = T_{c0} - T_{KT} = 2.5$ K. For BSCCO, it is 10 G. Our observed field dependence of the I-V relation is for $H \gg H_{c1}^0$. For field $H > H_{c1}^0$ but near T_{KT}, the flux lines fluctuate strongly and this fluctuation is due to the field-induced vortices. As discussed earlier, the Lorentz force generated by an external current acts on magnetically induced vortices in the same way as on thermally created pairs. Hence an excess dissipation below T_{KT} is produced due to the magnetically induced dissociated vortices.

An additional mechanism for the reduction of T_{KT} by magnetic field follows from the reduction of the density of Cooper pairs or the density of superconducting electrons n_s, which enters into the vortex-anitvortex pair energy through the London penetration depth, $\lambda\epsilon_{pair} = 2\epsilon_1 \ln(\rho/\xi)$ for $\rho \gg \xi$, where $\epsilon_1 = (\phi_0/4\pi)^2(d/\lambda^2)$ and λ^2/d is the effective penetration depth. The detailed mathematical treatment has been described elsewhere.[8] In high T_c superconductors, the combination of high-temperature, short coherence length and quasi 2D structure causes a large increase in the effect of thermal fluctuations.[8]

The Bardeen-Stephen behavior[12] of the flux-flow resistivity shows a linear relation in magnetic field. However, the observed magnetoresistance[7,13] shows a nonlinear behavior which does not support the flux-flow type of dissipation. Our observation of power-law behavior in the I-V characteristics and the jump in $\alpha(T)$ at $2T$ near T_c gives evidence for a KT transition. In view of the above observations, some of the models[14–16] which predict flux-flow or flux-creep types of behavior are not applicable.

The observed power law in the I-V curves below the KT transition in a magnetic field parallel to the *ab* plane in BSCCO crystal and a rapid decrease of $\alpha(T)$ up to $2T$ is related to an interplay of the in-plane vortex lines and 2D vortices created by a small component of a magnetic field parallel to the *c* axis.[7,13] This appeared because of a small misalignment to the *c* axis within the crystal.[15] As the dissipation caused by such misalignment follows a power-law behavior in I-V characteristics, the activation process is basically of a KT type. In a very small magnetic-field region a power-law dependence of the resistivity on the magnetic field was observed.[17,18] This is explained in terms of the creation of 2D vortices due to screening currents.[19] At $T < T_{KT}$, in a magnetic field, $H < 0.2$ T, the power-law behavior in I-V curves was observed and was explained in terms of the creation of 2D vortices which is due to the breaking of Abrikosov vortex lines by thermal fluctuations and transport current.[20] In our observation where the applied magnetic field is sufficiently high, we argued that the excess dissipation is due to the magnetic field-induced dissociated vortices.

The interlayer coupling in highly anisotropic superconductors such as BSCCO is so weak that 2D vortex-antivortex pairs are thermally activated within the CuO_2 plane.[17,21] The BSCCO crystal behaves as if the CuO_2 planes are decoupled,[15] therefore the magnetic field perpendicular to the plane penetrates completely and the interplane spaces are filled with Josephson vortex chains. The spacing between the chains d along the c axis is $c/2$ which is 1.5 nm for BSCCO. We observed a sharp change in magnetic-field dependent $\alpha(T)$ at $2T$ for BSCCO and BPSCCO crystals. The distance between each Josephson vortex in a chain when the magnetic field is $B_\perp = 2T$ is $\phi_0/B_\perp d = 0.67$ μm. If the interlayer flux lines are dense, the 2D vortex-antivortex pair creation in the CuO_2 planes is suppressed, which can be explained in terms of the interaction between the vortex pair and the interlayer flux lines. The creation of vortex-antivortex pairs which is similar to the creation of dislocation in the flux line lattice increases the elastic energy,[22] E_{el} by $E_{el}(R) \approx e_0 R/\sqrt{\Gamma}$, where Γ is the effective-mass anisotropy, R the size of the pair, and $e_0 = (\phi_0/4\pi\lambda_{ab})^2$ with λ_{ab} the penetration depth along the ab plane. The pair creation depends on the distance between the interlayer flux lines, l. It has been argued[13] considering the conditions for $R < l$ and $R > l$ that the significant suppression of pair creation occurs when l in the chains becomes ~ 0.7 μm. In view of the above, we observed a sharp change in magnetic-field dependent $\alpha(T)$ at about $2T$ (Fig. 8) for BSCCO and BPSCCO crystals, which shows that above $2T$ the significant suppression of vortex pair creation occurs.

In conclusion, we have observed power-law behavior in the I-V characteristics of BSCCO and BPSCCO crystals in zero and in applied magnetic fields. The dissipative behavior of these superconductors near T_c is explained by the motion of flux vortices produced by a magnetic field and by a KT transition of flux vortices in the superconducting planes. A Nelson-Kosterlitz jump in the temperature dependence of the power-law exponent clearly shows the evidence of a KT transition in which thermally induced pairs are dissociated. In a magnetic field, the KT transition occurs at lower temperatures as extra vortices of one sign are introduced. The critical value of the magnetic field above which the 2D vortex pairs are suppressed is about $2T$. The interaction of vortex pairs with interlayer flux lines has been considered in order to explain the magnetic-field dependence of the power-law exponent.

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