# Transition from intact to short decoupled vortices in the vortex liquid of $YBa_2Cu_3O_{7-\delta}$

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Superconducting transitions were studied in single-crystal $YBa_2Cu_3O_{7-\delta}$ with magnetic fields in the range 0.02–8 T applied along the $c$ axis and six contacts mounted on two $ab$-plane surfaces to measure voltages on opposite sides of the crystal. In the beginning of the transition curves, a change was observed at about 0.3 T from a high-field region, where vortices are preserved over the length of the crystal, to a low-field behavior where vortices move independently in different layers. In the high-field region a peak was observed in $V_{bot}$, which can be qualitatively understood in terms of breaking of long vortices by increased thermal fluctuations. At about 0.3 T we also observed a crossover in the magnetic-field dependence of an apparent activation energy from a $1/B$ behavior at high fields to $-\ln B$ at low fields. From the data in the low-field region new quantitative support is obtained for a Kosterlitz-Thouless-type transition where vortex-antivortex pairs dissociate and move independently in different layers of the crystal. The correlation length of these vortices is estimated to be 650±150 Å.

The vortex properties of high-temperature superconductors have opened for the discovery and study of a rich variety of new phenomena. The high transition temperatures and the often small pinning forces, combined with strong anisotropy and possibilities for pinning from defects due to the discrete nature of the atomic structure itself are some factors providing for the new regime of these investigations. In recent progress on studies of vortices it has been found that the vortex lattice melting transition is depressed by strong pinning by twin boundaries,[1] with evidence that this transition is first order in untwinned $YBa_2Cu_3O_{7-\delta}$ single crystals.[2] Within the vortex liquid a transition has been observed from activated to diffusive behavior with increasing magnetic field.[3] A multicritical point in the magnetic phase diagram of clean untwinned $YBa_2Cu_3O_{7-\delta}$ has also been suggested.[4] Usually moderately strong magnetic fields, $B$, are employed in these studies, in the range, say, 1–12 T, and the vortices are considered to be continuous flux lines, piercing the entire sample.

However, closer to the zero field $T_c$ there is evidence that thermally activated vortex-antivortex pairs govern transport properties. Such pancake-like vortices are loosely coupled between different layers of the crystal. Studies of superconducting fluctuations just above the zero resistance $T_c$ and measurements of current-voltage characteristics just below $T_c$ for[5] $YBa_2Cu_3O_{7-\delta}$ and[6] Bi 2:2:1:2 support a Kosterlitz-Thouless type phase transition in zero and small magnetic fields. Although such a picture is strictly valid only for two-dimensional (2D) systems the inclusion of anisotropy in 3D has been shown to lead to the same model.[7]

An interesting method to investigate the dimensionality of the vortices is to use a six terminal contact configuration, with two potential contacts measuring the potential drop, $V_{top}$, on the same crystal surface on which the current is fed, and two contacts at the opposite side, measuring $V_{bot}$. This method has been used recently for $Bi_2Sr_2CaCu_2O_{8-\delta}$ single crystals.[8–10] For a wide range in the $B$-$T$ phase diagram it was found that $V_{top} > V_{bot}$, giving direct indication that vortices have lost their integrity over the thickness of the sample and move independently in different layers of the crystal.

In the present paper we have studied vortex dimensionality in single-crystal $YBa_2Cu_3O_{7-\delta}$ in a six terminal configuration. Here the anisotropy is smaller than in Bi-based superconductors. In this way we can follow a transition from a high-field region above 0.5 T, where $V_{top} = V_{bot}$ at the lower part of the superconducting transitions and $V_{top} > V_{bot}$ at higher temperatures, to a low-field region with $V_{top} > V_{bot}$ for all $T$. Correspondingly we observed different field dependences of the activation energies in these two field regions with a crossover from $1/B$ to a $-\ln B$ behavior in the low-field region. From this result the correlation length of these thermally activated vortices can be estimated.

Single crystals of $YBa_2Cu_3O_{7-\delta}$ were grown by the self-flux method.[11] Approximately 1 g of $YBa_2Cu_3O_{7-\delta}$ was crushed and dissolved at a temperature of 1000 °C in the ratio 1:6.5 in a mixture of BaO and CuO (28–72 mol %). This charge was allowed to cool slowly in an $Y_2O_3$-stabilized $ZrO_2$ crucible in a horizontally directed temperature gradient of about 5–7 °C/cm. At the bottom of the crucible about 20 free standing single crystals could be recovered, with sizes up to $2\times2\times0.3$ mm$^3$. The crystals were further annealed for a few days at 450 °C in oxygen in order to optimize the oxygen content. There were twin boundaries at 45° to $a$ and $b$ axes in all crystals.

The resistive superconducting $T_c$ of these crystals varied between 91.0–91.5 K with transition widths (10–90 %) of 0.2 K. The normal state resistivity at 100 K was about 40 $\mu\Omega$ cm. $d\rho/dT$ in the normal state was about 0.3 $\mu\Omega$ cm/K.

A few single crystals with sizes in the range $1\times0.5\times0.1$ to $2\times2\times0.3$ mm$^3$ were chosen for the measurements. On the larger crystal six contacts were made as shown in the inset of Fig. 1. The contacts were

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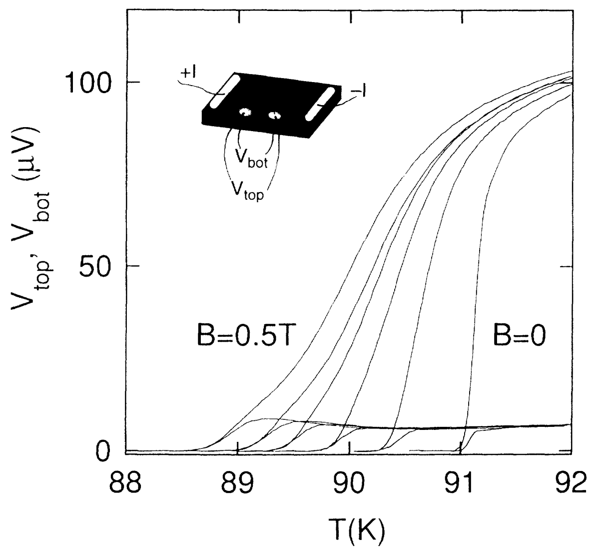


FIG. 1. Voltage drops over two $a$-$b$ plane surfaces of single-crystal $YBa_2Cu_3O_{7-\delta}$. Magnetic fields are from right to left 0, 0.1, 0.2, 0.3, 0.4, and 0.5 T. The inset shows the contact arrangement defining $V_{bot}$ and $V_{top}$.

prepared by applying small strips of silver paste, followed by heat treatment in flowing oxygen at 450 °C for one hour. 20 $\mu$m gold wires were attached to the silver strips with silver paste and the crystals were again heat treated for one hour in oxygen at 450 °C. The contact areas were about $0.8\times0.2$ mm$^2$ for the current contacts and about a quarter of this size for the voltage contacts. The resulting contact resistances were below 0.1 Ω.

The contact arrangement is shown in the inset in Fig. 1, and the results for $V_{top}$ and $V_{bot}$, on two opposite $a$-$b$ planes of the crystal are shown for some magnetic fields up to 0.5 T in the main panel of the figure. (Data for magnetic fields from 0.02 to 0.08 T have been omitted from this figure and Fig. 2 below in order not to overload them.) There is a large difference between the voltages at the top and bottom, amounting to about a factor of 15 in the normal state. This is a consequence of the strong anisotropy of the crystal. Some current partly follows a high resistivity path along the $c$ direction and the voltage drop from the smaller current is picked up by the contacts at the bottom. We also studied a thinner crystal with the same contact arrangement and observed a correspondingly smaller ratio between the two voltages. In a 30-$\mu$m thick Bi 2:2:1:2 crystal this ratio was about 8 in the normal state.[10]

The low-temperature region of the transitions is displayed more clearly in Fig. 2 for magnetic fields up to 8 T. For low fields $V_{top}$ is larger than $V_{bot}$ at all temperatures. With larger fields up to 8 T, $V_{top}=V_{bot}$ up to about 10% of the normal state voltage, while above that level $V_{top}>V_{bot}$, with a peak developing in $V_{bot}$ above about 0.3 T. Such a peak has been observed previously[8,9] in Bi 2:2:1:2 crystals and has been attributed to a knee in $\rho_c$ vs temperature close to the zero field $T_c$ and to an "upper" critical temperature corresponding to Josephson coupling of CuO bilayers, respectively. In Ref. 9 the peak was rapidly suppressed by a magnetic field in agreement with a Josephson coupling model. Our peak and that of Ref. 8 for Bi-based superconductors are apparently of a different nature since they first increase with increasing field, and then (in our case above 4 T), decrease slightly with magnetic field.

A simple physical picture of our observations is as follows. The larger current in the top layer produces a larger force on the vortices. Well below $T_c$, in the region with $V_{top}=V_{bot}$, vortices are thus dragged through the sample (in direction $\mathbf{j}\times\mathbf{B}$) with preserved integrity over the $c$-axis length of the sample, producing the same electric field $(-\mathbf{v}\times\mathbf{B})$ on all $a$-$b$ planes. With increasing temperature and/or decreasing magnetic field, thermal motion will break vortices into smaller parts, of correlation length $l_c$, say. Vortices at the bottom then experience a smaller force due to the smaller current there and $V_{bot}$ drops over the range where more and more vortices break up. Closer to the zero field $T_c$ the voltage range where $V_{top}=V_{bot}$ decreases since there is a rapidly decreasing number of rigid long vortices. Below about 0.3 T the peak disappears and $V_{top}>V_{bot}$ for all measurable voltages.

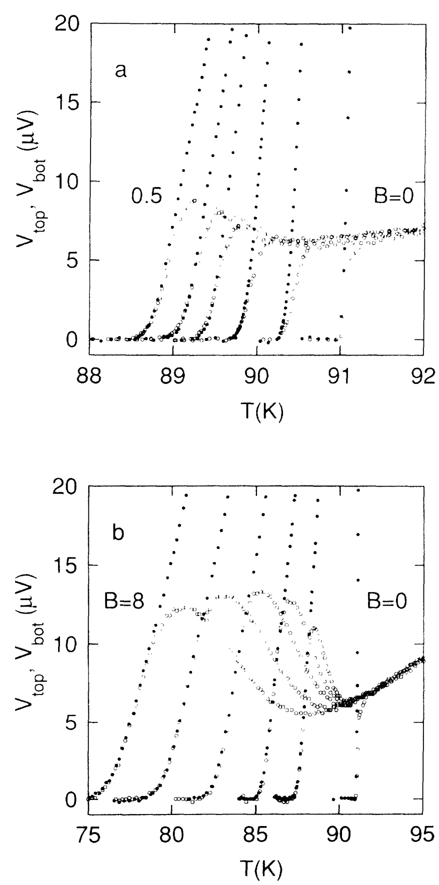


FIG. 2. Superconducting transitions on an expanded voltage scale. Full circles are $V_{top}$, open circles $V_{bot}$. Panel (a) shows magnetic fields from right to left of 0, 0.1, 0.2, 0.3, 0.4, and 0.5 T. In panel (b) the fields are from right to left 0, 1, 2, 4, 6, and 8 T.

The data for $V_{top}$ were analyzed in the form $\ln V$ vs $U/T$ to determine apparent activation energies, $U$. These analyses are shown in Figs. 3(a) and 3(b) for $B \leq 0.5$ T and $B \geq 1$ T, respectively. The voltage range which fits such a power law is of order 6% of the normal state voltage. These analyses were carried out by including all data from the measuring sensitivity of $\approx 0.2\ \mu$V up to the point where systematic deviations of the data below the fitted line were observable. Errors in the analyses of $U$ increase with decreasing field since $U$ increases and the temperature measurements become more crucial. Estimated errors are shown for some points in Fig. 4.

Such analyses give the magnitude and temperature dependence of a dominant contribution to the activation energy of vortex motion. The results in Fig. 4 show that there is a crossover in the field dependence of this activation energy from $1/B$ at high fields, to $-\ln B$ in the low-field region, suggesting different mechanisms for activated vortex motion in these field regimes. This transition region roughly coincides with the transition at small $V$ from $V_{bot} = V_{top}$ at high fields to $V_{bot} < V_{top}$ at low fields.

We now discuss Fig. 4 and show that the high-field limit is qualitatively consistent with previous results for activation of vortices over pinning centers, while the low-field behavior is in quantitative agreement with a model for thermal activation of vortex-antivortex pairs.

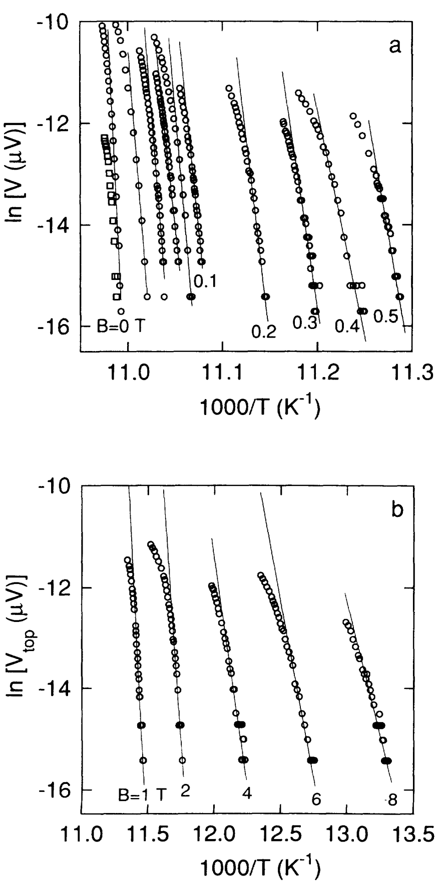


FIG. 3. Analysis of the low voltage region in the form of $\ln V$ vs $1/T$. Panel (a): low-field data. Magnetic fields between 0 and 0.1 T are 0.02, 0.04, 0.06, and 0.08 T. Squares for $B=0$ refer to $V_{bot}$, circles to $V_{top}$. Panel (b): high-field data for $V_{top}$.

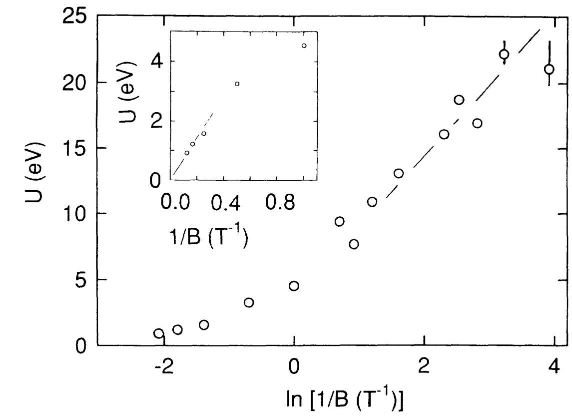


FIG. 4. The slope $U$ of the straight lines in Fig. 3 vs $\ln B$. A straight line is fitted to the low-field data. Error bars are shown on some points. The insets shows $U$ vs $1/B$ in the high-field region with a straight line describing data between 4 and 8 T.

The temperature dependence of an activation energy, will affect the slope evaluated from $\ln V$ vs $1/T$ at constant $B$, as pointed out previously[12] and our data in the high-field region should be corrected for this effect before evaluating an activation energy from $U$. However, in range 4–8 T, the data in the inset of Fig. 4 show that $U$ varies approximately as $1/B$ and in this field range the temperature dependence of a correction factor is small. This observed $1/B$ dependence is in qualitative agreement with the results on $YBa_2Cu_3O_{7-\delta}$ by Chien *et al.*[3] below a field $H_k(T)$, well above the region probed by our analyses. The magnitude of the observed field dependence, of about 7 eV $T$ from the inset of Fig. 4 would also seem reasonable, taking into account a temperature dependence $(1-T/T_c)^q$ with $q$ slightly larger than 1 and the large $T=0$ slope of 48 eV $T$ obtained in Ref. 3.

We now turn to the low-field region which is the main interest of our paper. Thermally activated independent vortices, which are uncorrelated in different layers are expected to give similar behavior of $V$ at all $a$-$b$ planes of the crystal. $V_{bot}$ was therefore analyzed in a similar way for some magnetic fields below 0.2 T. Since $V_{bot} < V_{top}$, the range for such a fit is smaller for $V_{bot}$ and the accuracy is reduced. However, the results confirm that straight lines parallel to those obtained for the corresponding $V_{top}(B)$ well describe the data for $V_{bot}(B)$. This can be seen from Fig. 3(a) where data for $V_{bot}$ at $B=0$ are shown as an example.

Jensen *et al.*[13] studied the influence of a magnetic field on vortex-antivortex pairs thermally activated above a Kosterlitz-Thouless type transition. They found an activation energy

$$E = E_c + \frac{l_c \phi_0^2}{2\pi\mu_0\lambda^2} \ln(\sqrt{\phi_0/B}\,/\xi) , \tag{1}$$

where $\phi_0$ is the flux quantum, $\lambda$ the in-plane penetration depth, and $\xi$ the corresponding Ginzburg-Landau correlation length. Here we have replaced the two-dimensional sample thickness with the correlation length

$l_c$. $E_c$ is the energy of a dissociated vortex-antivortex pair of length $l_c$.

$$E_c = 2l_c\phi_0^2\ln(\lambda/\xi)/(4\pi\mu_0\lambda^2) \ . \quad (2)$$

We estimated $l_c$ from Eq. (1) and the observed slope in Fig. 4. With $\lambda = 1400$ Å this gives $l_c = 650 \pm 150$ Å. Below some field of order $H_{c1}$ the second term in Eq. (1) is no longer valid. The activation energy can then be estimated from Eq. (2) with the value of $l_c$ obtained above. Taking $\xi = 15$ Å this gives $E_c = 47 \pm 12$ eV in fair agreement with the value of 35 eV obtained at $B = 0$ from Fig. 3.

Our result for the vortex correlation length can be compared with results obtained by other methods. Brunner and co-workers[14] studied a series of $YBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$ superlattices. By varying the thicknesses of the layers the coupling between them can be monitored. They found a lower limit for bulk $YBa_2Cu_3O_{7-\delta}$ to be $l_c = 450$ Å, consistent with our result.

From a study of the $I$-$V$ characteristics of $YBa_2Cu_3O_{7-\delta}$ single crystal Yeh and Tsuei found an effective sample thickness of $l_c/\varepsilon$ of 140 Å at the Kosterlitz-Thouless transition.[5] With the estimate of the dielectric constant $\varepsilon$ of 4.6 by Fiory *et al.*[15] this gives $l_c = 640$ Å in remarkable agreement with our result.

In summary we have studied the temperature and magnetic field dependence of the voltages at two *ab*-plane surfaces of single-crystal $YBa_2Cu_3O_{7-\delta}$. A transition is observed from high fields where $V_{bot} = V_{top}$ at the beginning of the transitions, to $V_{bot} < V_{top}$ for the full transitions in small fields, and in the high-field region a peak in $V_{bot}$ is observed when $V_{bot}$ starts to fall below $V_{top}$. This can be qualitatively understood in terms of the breaking up of coherent vortices along the full $c$-axis length of the sample, with independent vortices moving in different layers of the crystal. The crossover from $V_{bot} = V_{top}$ to the region where $V_{bot} < V_{top}$ at all temperatures is correlated with a smooth turnover in the apparent vortex activation energy from a $1/B$ dependence at larger fields to $-\ln B$ in the low-field range. In the low-field region quantitative agreement is obtained with a model[13] of thermally activated unbound vortex-antivortex pairs. Our result gives evidence that the superconducting transition of high-$T_c$ superconductors in zero and weak magnetic fields can be understood as a vortex unbinding Kosterlitz-Thouless type transition.

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