Pinning Strength Dependence of Mixed-State Hall Effect in $YBa_2Cu_3O_7$ Crystals with Columnar Defects

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The mixed-state Hall effect of twinned $YBa_2Cu_3O_7$ crystals after heavy-ion irradiation clearly showed that the strong pinning induced by columnar defects not only modifies the scaling behavior between the Hall resistivity and longitudinal resistivity, but affects the temperature dependence of the Hall conductivity. For the irradiated crystals, the scaling exponent at 4 T was found to be 1.5 ± 0.1 compared to 2.0 ± 0.2 for the unirradiated one. The temperature dependence of the Hall conductivity of the irradiated crystals exhibited a clear deviation from that of the unirradiated one at low temperatures.

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The Hall effect in the mixed state has been one of the unsolved problems in understanding the flux motion of type II superconductors. One of the most controversial phenomena has been a sign reversal of the Hall effect near the superconducting transition temperature T_c as temperature or magnetic field is varied [1–13]. This sign reversal of the Hall effect has been observed in most of the high-T_c superconductors (HTS) such as $YBa_2Cu_3O_x$ (YBCO) [1–7], $YBa_2Cu_4O_8$ [8], $Bi_2Sr_2CaCu_2O_8$ (BSCCO) [9], and $Tl_2Ba_2CaCu_2O_8$ (TBCCO) [10–12], as well as in some conventional superconductors [1,13]. Furthermore, a puzzling scaling behavior, $\rho_{xy} = A\rho_{xx}^{\beta}$, between the Hall resistivity ρ_{xy} and the longitudinal resistivity ρ_{xx} has been observed with scaling exponent $1.7 < \beta < 2$ in BSCCO crystals [9], TBCCO films [7,11], and YBCO films [2].

A number of theoretical predictions concerning the Hall effect in the mixed state have been presented. Dorsey and Fisher (DF) [14] first developed a scaling theory for the Hall resistivity near the vortex-glass transition. They showed that the Hall and longitudinal resistivities should scale with a universal power, which were observed by Luo *et al.* [2] in YBCO films, and further predicted that the nonlinear Hall electric field should scale with a universal power of current at the vortex-glass transition, later confirmed by Wöltgens *et al.* [3]. Then a phenomenological model resulting in $\rho_{xy} = A\rho_{xx}^2$ in the thermally assisted flux-flow region has been put forward by Vinokur *et al.* [15], where the coefficient A was assumed to be pinning independent. Their results seem to be in agreement with scaling exponents of both weakly pinned systems of BSCCO single crystals ($\beta = 2.0 \pm 0.1$) [9] and rather strongly pinned systems of heavy-ion irradiated TBCCO films ($\beta = 1.85 \pm 0.1$ and ~2.0) [7,11]. Recently, Wang, Dong, and Ting (WDT) [16] modified their earlier work [17] to develop a unified theory for the Hall effect including both the pinning effect and the thermal fluctuations. They [16] explained the scaling behavior and the anomalous sign reversal of the Hall effect by specially taking into account the backflow current due to pinning. In this case the scaling exponent β then changes from 2 to 1.5 as the pinning strength increases, and the coefficient A is no longer pinning independent.

A decisive experiment that can test the role of pinning on the Hall effect is to measure the Hall conductivity, or resistivity in some cases, before and after heavy-ion irradiation since columnar defects formed along the heavy-ion tracks are very effective pinning centers [18]. The first attempt was made by Budhani, Liou, and Cai [11] on Ag-ion irradiated TBCCO films. They observed that the scaling behavior remains unaffected even after irradiation and the sign anomaly diminishes with increasing defect density. So they suggested that pinning is not responsible for the sign reversal. Later Samoilov *et al.* [7] measured the Hall conductivity of YBCO single crystals and TBCCO films before and after Pb-ion irradiation, and argued that the pinning enhancement does not modify the behavior of the Hall conductivity. In this Letter we report a systematic study of the mixed-state Hall effect of twinned YBCO single crystals before and after heavy-ion irradiation and will unambiguously show that strong pinning induced by heavy-ion irradiation indeed modifies the mixed state Hall effect in YBCO crystals.

The single crystals of YBCO were grown by the standard flux technique. The crystals were cleaved by bar-shaped samples suitable or Hall effect measurements. The crystals have typical dimensions of $1 \times 0.8 \times 0.03$ mm^2. The electrical contacts ($<0.1\ \Omega$) were made by Ag evaporation followed by annealing at 400 °C in O_2 atmosphere for 12 h. The samples from the same batch were irradiated at 0 °C by 740 MeV Sn and Xe ions, which were produced by the Argonne Tandem Linear Accelerator System at the Argonne National Laboratory. The ion beam was aligned approximately parallel to the c axis of the samples, and a thin gold foil was inserted in the beam line to make sure a uniform beam profile appeared over the sample width. The irradiation doses of 5×10^{10}, 1×10^{11}, and 1.5×10^{11} ions/cm^2 were chosen so that the matching fields B_ϕ correspond to ~1, 2, and 3 T, respectively. YBCO crystals of 1 and 2 T doses are irradiated with Sn ions, whereas 3 T dose crystal is irradiated with Xe ions. The Hall resistivity ρ_{xy} and longitudinal resistivity ρ_{xx} were measured by standard five-probe dc method and magnetic fields were applied parallel to the c axis of YBCO crystal. The current density used for these measurements was ~20 A/cm^2. Cryogenic coaxial cables are used for voltage leads to minimize the extrinsic noise pickup.

Typical resistive transitions of two crystals, $B_\phi = 0$ (unirradiated) and 2 T, are shown in Fig. 1 as a function of reduced temperature $t = T/T_c$ in magnetic fields of 2 and 4 T. Enhancement of the onset temperature of ρ_{xx} in magnetic fields due to enhanced pinning is clearly visible, in agreement with the related works [7,11] on samples containing columnar defects. The figure is presented in reduced temperature t and reduced resistivity $r \equiv \rho_{xx}(T)/\rho_{xx}(T_c)$ in order to account for the difference of T_c and normal state resistivity [19]. T_c's determined as the peak temperatures of dR/dT curves are 93.8 and 93.1 K, respectively, for $B_\phi = 0$ and 2 T dose crystals. At higher temperature where $r > 0.6$, longitudinal resistivities of both samples are closely together, but they begin to deviate for $r < 0.6$, showing the region of effective pinning due to columnar defects. Note that kink structure, known as the characteristics of twin-boundary pinning [20], near the foot of transition of the unirradiated sample is no longer observable in the irradiated one. Similar disappearance of kink in electron-irradiated YBCO crystal has been reported [19]. The other crystals with $B_\phi = 1$ and 3 T dose showed similar behavior.

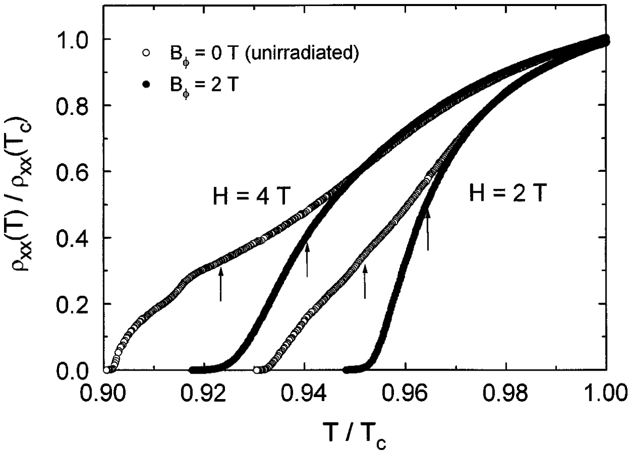

FIG. 1. Longitudinal resistivity of two twinned $YBa_2Cu_3O_7$ single crystals, $B_\phi = 0$ (unirradiated, open symbols) and 2 T dose (solid symbols), shown as a function of reduced temperature $t = T/T_c$ in magnetic fields of 2 and 4 T. Arrows indicate the negative peak positions of the Hall resistivity shown in Fig. 2.

The corresponding Hall coefficients ρ_{xy}/B are shown in Fig. 2. Sign reversal of the Hall effect was observed in both irradiated and unirradiated samples as temperature is lowered. Here again ρ_{xy}/B curves for both samples closely follow each other for $r > 0.6$ similar to the case of the longitudinal resistivity. After irradiation the onset of ρ_{xy} as well as the negative peak positions shift to higher temperature, and the depths of the negative peaks are reduced. The locations of negative peaks of ρ_{xy}/B are shown as arrows in Fig. 1.

In Fig. 3, we show the scaling behavior between the Hall resistivity ρ_{xy} and longitudinal resistivity ρ_{xx}, $\rho_{xy} = A\rho_{xx}^\beta$, for crystals of $B_\phi = 0$, 1, 2, and 3 T dose. The scaling behavior holds in the temperature region below the negative peak of ρ_{xy} where pinning is effective, i.e., $r < 0.4$. The striking difference between the irradiated and unirradiated samples is their scaling exponent β. The scaling exponent of the unirradiated crystal showed gradual increase with the applied magnetic field. For 1 T, β is 1.5 ± 0.1, but increases to 1.75 ± 0.1 for 2 T (not shown in the figure), and becomes 2.0 ± 0.2 for 3 T and higher fields as shown in Fig. 3(a). Also shown are two solid lines of $\beta = 1.5$ and $\beta = 2.0$ for the reference. For all three irradiated crystals, however, field independent $\beta = 1.5 \pm 0.1$ was observed for fields from 2 to 4 T as shown in Figs. 3(b)–3(d). We also measured the Hall resistivities for 6 T field, but the signal to noise ratio from

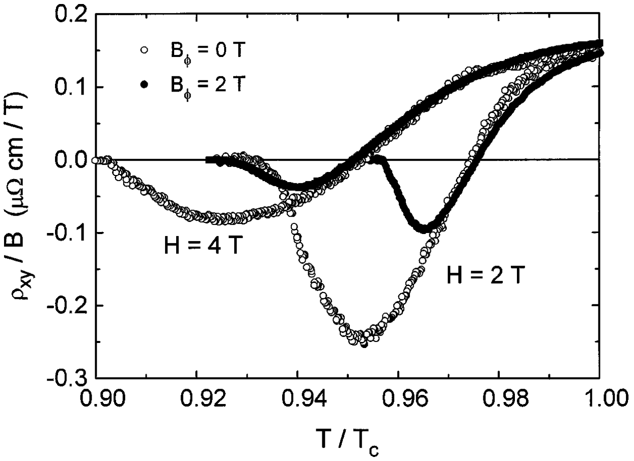

FIG. 2. Hall coefficient of two twined $YBa_2Cu_3O_7$ single crystals, $B_\phi = 0$ (unirradiated, open symbols) and 2 T dose (solid symbols).

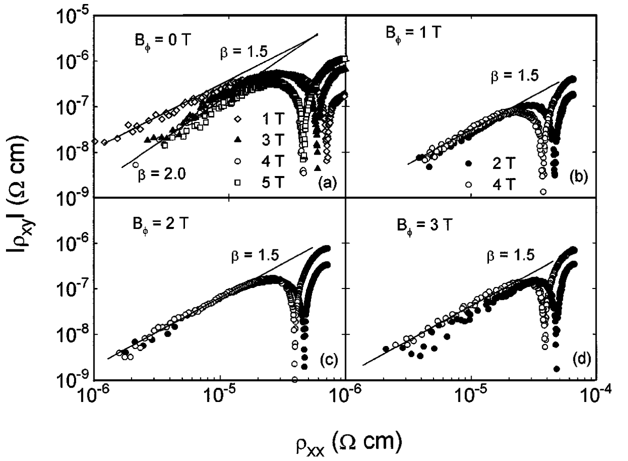

FIG. 3. Scaling behavior, $\rho_{xy} = A\rho_{xx}^{\beta}$, between the Hall resistivity ρ_{xy} and longitudinal resistivity ρ_{xx} of $YBa_2Cu_3O_7$ crystals with $B_\phi = 0$ (a), 1 (b), 2 (c), and 3 T dose (d). Solid lines are power-law dependences of $\beta = 1.5$ and 2.

the irradiated samples was not large enough to estimate β with reasonable accuracy.

According to Vinokur *et al.* [15], scaling behavior of the Hall resistivity in the mixed state of HTS is a general feature of any vortex state in the presence of the quenched disorder and thermal noises. Using the force balance equation for a stationary moving vortex, they argued that pinning just renormalizes the drag force term, not affecting the Hall conductivity term. Their main results are that Hall conductivity σ_{xy} ($\approx \rho_{xy}/\rho_{xx}^2$) does not depend on disorder and the scaling exponent β is exactly 2, which can be summarized as

$$\rho_{xy} = \alpha\rho_{xx}^2/\Phi_0 B\,, \tag{1}$$

where Φ_0 is the flux quantum, and α is a pinning independent parameter related to the Hall angle.

On the other hand, WDT [16] recently developed a new theory for the flux motion for the mixed-state Hall effect. They included both pinning-induced backflow and thermal fluctuations in the force balance equation. Then, an additional transverse term proportional to $\mathbf{F}_p \times \mathbf{n}$ with $\mathbf{F}_p$ pinning force and $\mathbf{n}$ a unit vector in the direction of magnetic field, induced due to the backflow current inside the normal core, appears in the drag force. This transverse term is the main difference between two models. After time averaging the vortex velocity, the Hall scaling is given by

$$\rho_{xy} = (\beta_0\rho_{xx}^2/\Phi_0 B)\{\eta(1-\overline{\gamma}) - 2\overline{\gamma}\Gamma(\nu_L)\}\,, \tag{2}$$

where $\beta_0 = \mu_m H_{c2}$ with μ_m being the mobility of the charge carrier and H_{c2} being the upper critical field, η is the usual viscous coefficient, $\overline{\gamma} = \gamma(1 - \overline{H}/H_{C2})$ is proportional to γ, the parameter describing contact force on the surface of core with $\overline{H}$ the average magnetic field over the core, and $\Gamma(v_L)$ is the coefficient of the time average of pinning force $\langle\mathbf{F}_p\rangle = -\Gamma(v_L)\boldsymbol{v}_L$. When $\gamma \sim 1$ in the region of relatively high temperatures [16], the negative Hall effect appears if pinning is not negligible.

For the Hall scaling behavior, there are two distinct regimes according to Eq. (2). For systems with weak pinning, that is $\Gamma(v_L) \ll \eta\overline{H}/H_{c2}$, Eq. (2) becomes $\rho_{xy} \sim A\rho_{xx}^2$, resulting in the same scaling exponent as Eq. (1). But in case of strong pinning, that is, $\Gamma(v_L) \gg \eta\overline{H}/H_{c2}$, the scaling exponent β is no longer 2. Since $\Gamma(v_L) \sim v_L^{-1/2}$ in the strong pinning case [21], scaling behavior modifies to $\rho_{xy} \sim A\rho_{xx}^{1.5}$. Between two limiting regimes, $1.5 < \beta < 2.0$ is expected [16].

Comparing our results in Fig. 3 with both theories, we find that the model by WDT [16] explicitly including the pinning-induced backflow effect is in better agreement with the data. For the unirradiated crystal, the experimental results indicate that for 1 T or lower fields most of the vortices can be pinned strongly, in a small current limit, by the twin boundaries or other intrinsic defects; thus β is 1.5 of the strongly pinned system. But for fields >2 T where the density of vortices sufficiently outnumbers the density of pinning centers, β becomes 2 presumably because this case is closer to the relatively weakly pinned system. For the irradiated crystals with the additional columnar defects present, our data show that most of the vortices are strongly pinned up to 4 T even in a $B_\phi = 1$ T sample so that β becomes 1.5. The WDT model could imply that β can approach 2.0 for fields $\gg B_\phi$ for irradiated crystals. However, the interaction between vortices, which should be important in high fields, is not included in the WDT model.

Our results of the unirradiated crystals are not inconsistent with the earlier work on YBCO films. The difference is that films usually contain a higher density of strong pinning centers than twinned crystals; thus β for films seems to remain unchanged even in higher fields. Luo *et al.* [2] reported that $\beta = 1.7 \pm 0.2$ for all fields >1.4 T. Wöltgens *et al.* showed that scaling behavior obeys $\rho_{xy} \sim A\rho_{xx}^{2.0\pm0.2}$ near the vortex-glass transition over a wide range of current densities [3]. However, in a small current regime that corresponds to the present window of the experiment, the data clearly show that the scaling exponent is less than 2.0, consistent with our results.

Similar measurements on epitaxial TBCCO films containing columnar defects were made by Budhani, Liou, and Cai [11] and Samoilov *et al.* [7]. They both observed that the same scaling behavior persists even after irradiation. Since the vortex structure of TBCCO is known to be two dimensional in the region where the scaling law holds and thin films inherently contain higher defects, the pinning enhancement may not be as dramatic as the case of YBCO crystals. No work has ever been reported on the scaling behavior of the Hall resistivity in YBCO crystals after heavy-ion irradiation.

Samoilov *et al.* [7] also reported the Hall conductivity of YBCO single crystals before and after Pb-ion irradiation (Fig. 3 of Ref. [7]). Since the Hall conductivity according to Vinokur *et al.* [15] is given as $\sigma_{xy} = \rho_{xy}/\rho_{xx}^2 = \alpha/B\Phi_0$, one can examine the validity of Eq. (1), i.e., independence of α on pinning, by plotting σ_{xy} before and after irradiation. In their plot, however, σ_{xy} is shown as a function of temperature. Although their data are definitely valid, the conclusion that σ_{xy} is unaffected by irradiation based on their plot seems misleading. We argue that in order to compare the physical properties of samples with different T_c, one should plot the data in the *reduced* temperature scale, not in the real temperature scale. Thus we plot the Hall conductivity of $B_\phi = 0$ and 2 T dose as a function of *reduced* temperature in various magnetic fields in Fig. 4. The Hall conductivity of $B_\phi = 2$ T follows that of the unirradiated one until it sharply deviates at low temperatures. This unambiguous drop at low temperatures is further evidence of the dependence on the pinning of mixed-state Hall effect. We point out that if the data by Samoilov *et al.* [7] were replotted as a function of *reduced* temperature after correcting the T_c decrease of ~0.3 K after irradiation, their Fig. 3 would be consistent with our Fig. 4. The direction of deviation of σ_{xy} after irradiation is also consistent with Eq. (2). The presence of stronger pinning will make σ_{xy} more negative, and this is exactly what we observed. As a final note, it is meaningful to investigate the relationship between the critical exponents of the longitudinal and the Hall fields near the vortex-glass transition within the context of the DF model [3,14] for the crystal samples, but such an attempt was limited by the sensitivity of the conventional transport technique since it required much higher sensitivity to probe the vortex-glass scaling behaviors in crystals.

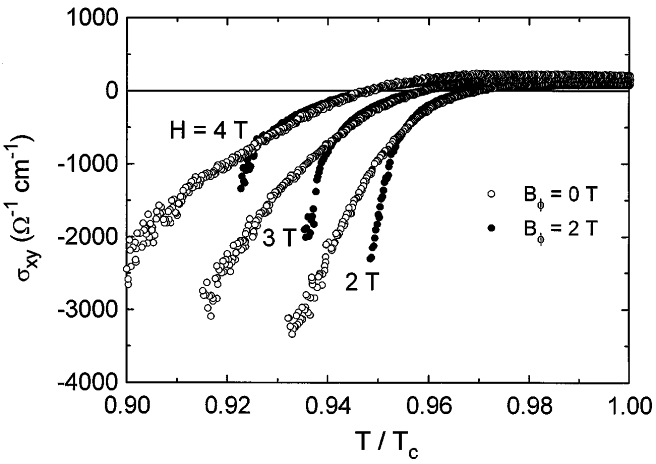

FIG. 4. Hall conductivity of $YBa_2Cu_3O_7$ crystals with $B_\phi = 0$ (open symbols) and 2 T dose (solid symbols) as a function of reduced temperature in magnetic fields of 2, 3, and 4 T. The Hall conductivity of $B_\phi = 2$ T shows a sharp deviation from the unirradiated one at low temperatures.

In summary, we showed that strong pinning induced by heavy-ion irradiation indeed modifies mixed-state Hall effect in YBCO crystals. The scaling exponent of the Hall effect for the irradiated crystals was found to be $\beta = 1.5 \pm 0.1$, different from that of the unirradiated crystal. The Hall conductivity was also changed after irradiation. These results are in good agreement with the recent theory including both the backflow effect due to pinning and thermal fluctuations where β should decrease from 2.0 to 1.5 as the pinning strength increases.

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