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Magnetoresistance and Hall Effect Study of Electron- and Hole-Doped Cuprate Superconductors†

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Hall effect measurements on single crystals of the hole-doped systems $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}(\delta \approx 0.05)$ and $YBa_2Cu_3O_y$ as a function of x and y, respectively, showed that the Hall conductivity σ_{xy} vs B data in the mixed state could be described by the expression $\sigma_{xy} = C_1/B + C_2B$, where the two terms are associated with motion of the magnetic vortices and the quasi-particles in the vortex cores, respectively, and the parameters C_1 and C_2 are functions of x, y, and T. Magnetoresistance measurements on epitaxial thin films of the electron-doped superconductor $Nd_{1.85}Ce_{0.15}CuO_{4\pm\delta}$ with varying oxygen content in magnetic fields $B \parallel$ c revealed (a) critical scaling of the electrical resistivity data consistent with a vortex-glass transition for a film with an optimum $T_c \approx 22$ K and (b) a characteristic anomaly that develops with increasing field for $T < 2$ K for an over-oxygenated film with $T_c \approx 10$ K.

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I. Introduction

The pinning and dynamics of fluxoids in high T_c cuprate superconductors constitute a fundamental problem of considerable interest which also has important implications for technological applications of superconductivity. In this paper, we briefly describe Hall effect and magnetoresistance measurements we recently performed on hole-doped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ and $YBa_2Cu_3O_y$ superconductors and electron-doped $Nd_{1.85}Ce_{0.15}CuO_{4\pm\delta}$ superconductors in order to study the "negative Hall anomaly" and the vortex-glass transition in the mixed state, respectively. A more detailed account of this work can be found elsewhere [1,2].

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II. Experimental details

The Hall-effect studies were carried out on six $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ($0 \leq x \leq 0.42$; $\delta \approx 0.05$) and four $YBa_2Cu_3O_y$ ($6.65 \leq y \leq 6.84$) single crystals, grown by methods described elsewhere [3,4]. In our measurements, the magnetic field B was applied parallel to the c-axis ($B \parallel c$), and electrical current, with the same current density $J \perp B$ of 100 A/cm^2, passed through all of the samples. Magnetoresistivity experiments were performed on c-axis oriented $Nd_{1.85}Ce_{0.15}CuO_{4\pm\delta}$ films that were prepared by pulsed laser deposition in N_2O [5]. The oxygen content was varied by annealing the films in either vacuum ($\approx 1 \times 10^{-5}$ torr) or oxygen ($\approx$ 400 torr) at 450-600°C. Magnetoresistance measurements were performed in magnetic fields of up to 80 kOe oriented parallel ($B \parallel c$) or perpendicular ($B \perp c$) to the tetragonal c-axis of the films with the current I flowing in the ab plane.

III. Results and discussion

III-1. Mixed-state Hall effect of Pr-substituted and oxygen-deficient $YBa_2Cu_3O_{7-\delta}$

Figure 1(a) shows Hall resistivity ρ_{xy} vs B data in the vicinity of T_c for an $YBa_2Cu_3O_{7-\delta}$ crystal. While ρ_{xy} is positive and linear in B for T > T_c, it displays the "negative Hall anomaly" a few degrees below T_c. The region of negative ρ_{xy} shifts to higher fields at lower temperatures. Shown in the inset of Fig. 1(a) are ρ_{xy} and the longitudinal resistivity ρ_{xx} vs B, measured at 81 K. The onset of the negative Hall signal occurs at a slightly higher field, compared to the field where ρ_{xx} starts to deviate from zero, while the negative ρ_{xy} extends over a region where ρ_{xx} *increases* rapidly with increasing field. We observed a similar ρ_{xy} vs B profile for all the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ and $YBa_2Cu_3O_y$ single crystals with $T_c >$ 70 K. For samples with $T_c \leq$ 70 K, only a positive Hall signal was observed [1,6]. Jia et al. reported the presence of the negative Hall anomaly in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals with $x < 0.2$ [7].

Figure 1(b) contains a plot of the magnitude of the maximum value Δ of the negative Hall resistivity ρ_{xy}, extracted from ρ_{xy} *vs B* curves [see the inset to Fig. 1(a) for the definition of Δ], vs the reduced temperature T/T_c, for both systems. The two interesting features of all these curves are the following: (1) for both systems, Δ is nonzero over the same reduced temperature range ($0.87 \lesssim T/T_c \leq 1$) with the onset of pinning occurring at $T/T_c \approx 0.87$ for all the single crystals with $T_c \gtrsim 70$ K, and (2) Δ_{max} scales with T_c and decreases monotonically, as shown in the inset; a linear fit of the data with $\Delta_{max} \neq 0$ extrapolates to $\Delta_{max} = 0$ at $T_c = 75$ K. This suggests that the negative anomaly in ρ_{xy} would not be observable for samples with $T_c \lesssim 75$ K. The close similarity of the profiles of Fig. 1(b) and the monotonic evolution of Δ_{max} with T_c for both systems we have studied indicate that the negative anomaly has an intrinsic origin and is not caused by extrinsic factors such as inhomogeneities in oxygen content or Pr concentration. Furthermore, the suppression of Δ_{max} with decreasing T_c suggests that the Hall anomaly is not due to flux pinning since, for low x values, the pinning potential increases with increasing x (decreasing T_c) [8]. Within the context of flux pinning models, an increase in the magnitude of the negative Hall voltage would then be expected, contrary to the behavior observed experimentally.

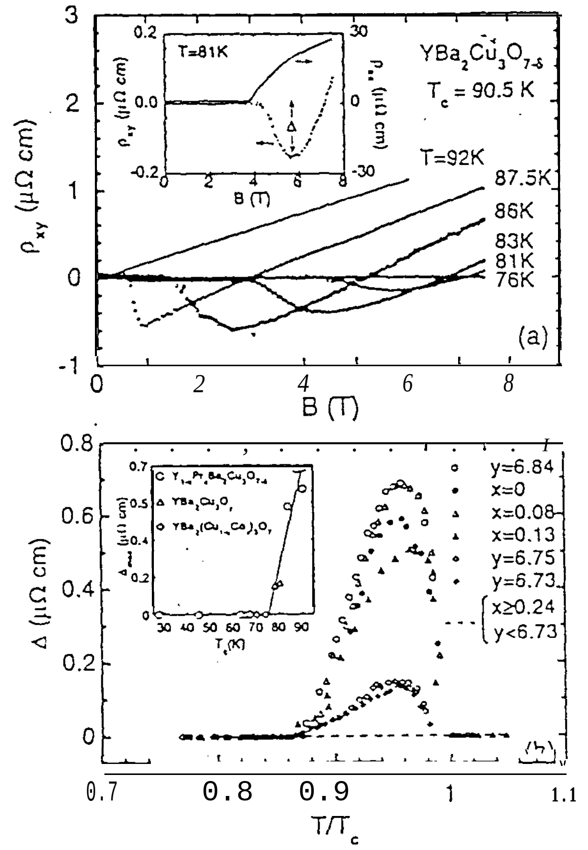

FIG. 1. (a) Hall resistivity ρ_{xy} vs magnetic field B in $YBa_2Cu_3O_{7-\delta}$ for temperatures in the vicinity of T_c. Inset: Hall resistivity ρ_{xy} and longitudinal resistivity ρ_{xx} vs B at 81 K. (b) Magnitude of the maximum value Δ of $\rho_{xy}(B)$ for single crystals of $YBa_2Cu_3O_y$ and $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, taken at different temperatures, vs reduced temperature T/T_c. The samples are listed in the legend in the order of decreasing T_c. The maximum value Δ_{max} is plotted in the inset vs T_c. (After Ref. 1.)

A convenient method for analyzing the Hall-effect data in the superconducting state near T_c has been proposed by Dorsey [9], Kopnin, Ivlev, and Kalatsky [10], and Geshkenbein and Larkin [11]. In the time-dependent Ginzburg-Landau formalism, they showed that the Hall conductivity in the mixed state can be expressed as the sum of superconducting σ^s_{xy} and normal σ^n_{xy} contributions:

$$\sigma_{xy} = \sigma^s_{xy} + \sigma^n_{xy} = C_1/B + C_2B. \tag{1}$$

In Eq. (1), σ^s_{xy} arises from the motion of the magnetic vortices, while σ^n_{xy} is associated with the motion of the quasiparticles in the vortex cores. If the coefficients C_1 and C_2 have different signs, then the Hall effect can change sign as B is varied, as observed experimentally.

The Hall conductivity data are described well by Eq. (1) for the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ crystals. This is illustrated in Fig. 2 which contains linear fits of $\sigma_{xy}B$ vs B^2 data for single crystals with x = 0.08 and x = 0.42, respectively, at various temperatures T < T_c and for fields $B_m \le B \lesssim 7$ T, where B_m is the field below which the Hall resistivity starts bending over, presumably due to flux pinning. The negative sign anomaly in σ_{xy} is present for the $Y_{0.92}Pr_{0.08}Ba_2Cu_3O_{7-\delta}$ sample, which is consistent with C_1 and C_2 > 0 and absent for the $Y_{0.52}Pr_{0.48}Ba_2Cu_3O_{7-\delta}$ sample where both C_1 and C_2 are positive. The Hall conductivity data for $YBa_2Cu_3O_y$ (y = 6.84, 6.75) are described well by Eq. (1) with an additional field-independent term C_3 included. The $\sigma_{xy}(B)$ data for the $YBa_2Cu_3O_y$ crystals with y = 6.73 and 6.65 show an even more complicated field dependence which we suspect is sample dependent.

The temperature dependence of the coefficient C_1 follows a systematic trend with T_c: C_1 is negative (positive) for samples which display (do not display) the negative ρ_{xy} anomaly. Over the same reduced temperature range T/T_c, the magnitude of C_1 is considerably larger for the samples with C_1 < 0 with an equally good fitting of the data to Eq. (1) for low and high values of x. The temperature dependence of C_1 was found to follow the form $C_1 = A(1 - T/T_c)^\alpha$ where α ranges from 1.4 to 2.8. C_1 vanishes within experimental error for T $\le T_c$. For $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, C_2 in the superconducting state is positive and approximately proportional to T_c/T for all x values with a slope which decreases with

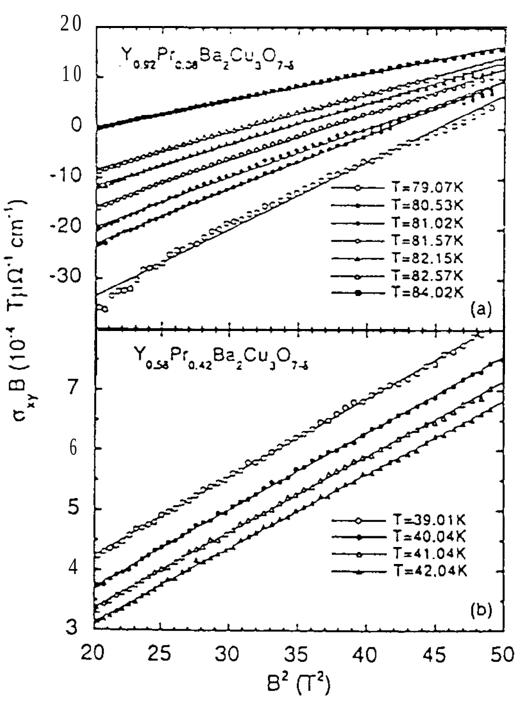

FIG. 2. $\sigma_{xy}B$ vs B^2 data for (a) $Y_{0.92}Pr_{0.08}Ba_2Cu_3O_{7-\delta}$ and (b) $Y_{0.58}Pr_{0.42}Ba_2Cu_3O_{7-\delta}$ single crystals measured at different temperatures. The solid lines are fits to the data with Eq. (1). (After Ref. 1.)

increasing x, while, in the normal state, C_2 is positive, small, and has a weaker temperature dependence. For the two $YBa_2Cu_3O_y$ single crystals, C_2 increases with decreasing T, displays a maximum for $T = T_c$, and then decreases with decreasing T. C_3 is positive in the superconducting state and decreases with increasing T to zero within experimental error at $T = T_c$.

Several other groups have recently analyzed their Hall effect data for the mixed state of cuprate superconductors in terms of Eq. (1) or the modified form of Eq. (1) including the field-independent C_3 term [12-14]. It is noteworthy that Feigel'man et al. [15], have proposed a mechanism for the sign change of the Hall effect in the flus-flow region which results from the difference between the electron densities at the center and far outside the vortex cores.

III-2. Magnetoresistivity of superconducting thin films of $Nd_{1.85}Ce_{0.15}CuO_{4\pm\delta}$

The magnitude of the zero-field ab-plane normal state electrical resistivity ρ_{ab} of $Nd_{1.85}Ce_{0.15}CuO_{4\pm\delta}$ thin films is greater for both deoxygenated and oxygenated films, when compared to that of the optimum doped film. This behavior is considerably different from that of other cuprate superconductors, including $Nd_{2-x}Ce_xCuO_{4-y}$ (NCCO) with varying Ce concentration, where a monotonic decrease of the resistivity with increasing carrier density was observed [16].

In Fig. 3 we show the temperature dependence of ρ_{ab} in different magnetic fields $H \parallel c$ for an optimum doped film with $T_c \approx 22$ K and an over-oxygenated film with $T_c \approx 10$ K. For the over-oxygenated film, we observe the development of an anomaly in the T-dependences of ρ_{ab} with increasing field $H \parallel c$ which initially manifests itself as a change in curvature from positive to negative for $H \geq 12$ kOe, becoming more pronounced for $H \gtrsim 20$ kOe. For fields above 20 kOe, an upturn in $\rho_{ab}(T)$ below ~ 2 K produces a minimum in $\rho_{ab}(T)$, which at lower temperatures ($T \lesssim 0.6$ K) is followed by an abrupt drop in $\rho_{ab}(T)$. The position of the onset of this drop, marked by a local maximum in the resistivity, is only slightly affected by the increasing field. What is striking about this peculiar behavior is the fact that it resembles the anomalies reported for NCCO single crystals with varying Ce concentration and reduced T_c's (Ref. 18) extremely closely, especially in the case of a crystal with $T_c \approx 11$ K, where the agreement is semiquantitative. Considering possible explanations for this anomaly, the existence of a high-temperature vortex melting transition followed by a vortex glass transition at lower temperatures [18] seems rather unlikely given the considerable amount of disorder in the films. The strong field dependence of the upper transition and the weak influence of a field on the lower transition argue against an interpretation in terms of intrinsic granularity [19]. The strong similarity of the anomaly observed in NCCO crystals and films, on the other hand, implies an internal origin, which — as already suggested in Ref. 18 — may be magnetic in nature, considering the fact that the Nd^{3+} ions order antiferromagnetically in the relevant temperature interval below ~ 2 K.

According to the vortex glass model [20], in the scaling regime the resistance R should vanish as $R \sim |T - T_G|^{\nu(z-1)}$. Plotting $(d\ln\rho/dT)^{-1} \propto (T - T_G)/[\nu(z-1)]$ vs T for a film with $T_c \approx 22$ K in different external fields $H \parallel c$, we observe a linear dependence in the low resistivity range, where, the slope defines the critical exponent $\nu(z-1)$, the intercept with the T axis defines T_G, and T^* marks the characteristic temperature at which the data start to deviate from the linear dependence, defining the width of the critical scaling regime.

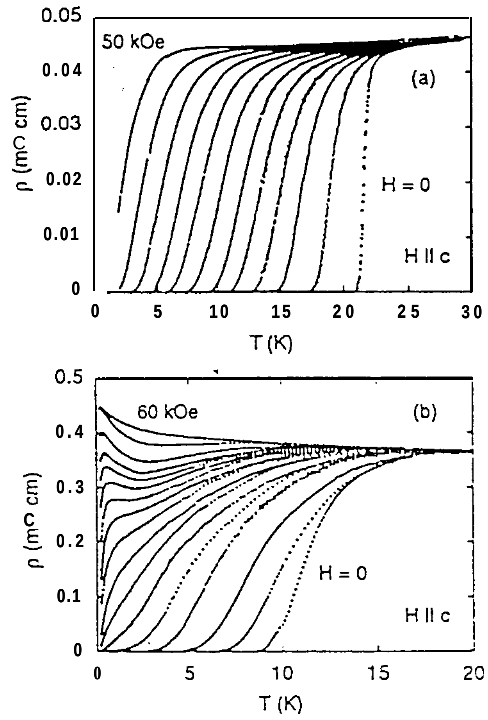

FIG. 3. Temperature dependence of the electrical resistivity ρ(T) for NCCO films with $H\|c$. (a) $T_c \approx 22$ K (z-prepared). The external magnetic field H for the different ρ(T) curves is 0, 2, 6, 10, 14, 20, 25. 30, 35, 40, 43, and 50 kOe, respectively. (b) $T_c \approx 10$ K (over-oxygenated). The external magnetic field H for the different ρ(T) curves is 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26. 30, 40, and 60 kOe, respectively.

Neither the slope of the linear fits to the critical regions nor the width of the temperature interval $T^* - T_G$ where this description appears to be appropriate seem to exhibit a dramatic field dependence. We found $\nu(z-1) \approx (6.3 \pm 1.5)$ with no clear correlation with the field. The field dependences of T_G and T^* are described by power laws: $H(T_G)$ a $(1 - T_G(H)/T_{c0})^{2.0}$ and $H(T^*)$ a $(1 - T^*(H)/T_{c0})^{1.7}$, respectively.

To obtain information about the upper critical field, we performed an analysis of the fluctuation conductivity σ_{fl}, utilizing the high-field limit scaling expressions derived within the framework of the Ginzburg-Landau fluctuation theory using the Hartree approximation [21], where σ_{fl} is a universal function of a scaling variable containing $H, T, T_{c0} = T_c(H=0)$, and H,,(O). Unfortunately, from this analysis it is not possible to extract $T_c(H)$, but only H,,(O), provided T_{c0} is known. To obtain T_{c0}, a similar scaling analysis was performed, assuming σ_{fl} to be described by the sum of an Azlamazov-Larkin and a Maki-Thompson term in zero field. We find $T_{c0} = (21.9 \pm 0.1)$ K and H,,(O) $= (80 \pm 5)$ kOe, which corresponds to an initial slope of the upper critical field vs temperature curve $(dH_{c2}/dT)|_{T=T_{c0}} =$ (-3.7 $\pm$ 0.3) kOe/k and yields a zero field in-plane coherence length $\xi_{ab}(0) = (64 \pm 2)$ Å for a film with $T_c \approx 22$ K and $H \|$ c. Based on the expression $H_{c2}^*(0) = 0.69 T_{c0}(dH_{c2}/dT)|_{T=T_{c0}}$ for

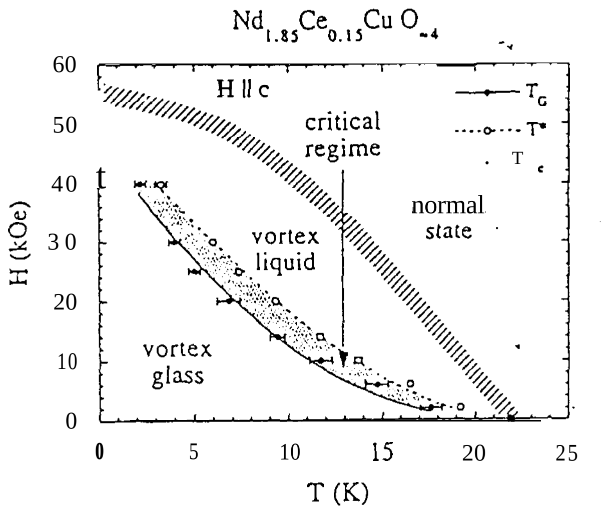

FIG. 4. Magnetic field H vs temperature T phase diagram for the NCCO film with $T_c \approx 22$ K and $H \parallel c$. The solid and dashed lines are fits to power laws $H(T_G) \propto (1 - T_G(H)/T_{c_0})^{2.0}$ and $H(T^*) \propto (1 - T^*(H)/T_{c_0})^{1.7}$ respectively. Squares mark the zero-field transition temperature T_{c_0}, and the zerc-temperature upper critical field $H_{c_2}(0)$, respectively. The dashed area indicates the region where the mean field upper superconducting transition is expected.

the orbital critical field $H^*_{c_2}(0)$, we obtain $H^*_{c_2}(0) = (55 \pm 3)$ kOe. These values, together with the results for $T_G(H)$ and $T^*(H)$ were used to construct the $H - T$ phase diagram of Fig. 4.

IV. Summary

The maximum value A of the negative Hall resistivity ρ_{xy} of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ($0 \leq x \lesssim 0.13$) and $YBa_2Cu_3O_y$ (6.735 $y \leq 6.84$) single crystals scales with T/T,, exhibiting a maximum Δ_{max} for $T/T_c \approx 0.96$ and vanishing for $T/T_c \lesssim 0.87$. Δ_{max} scales with T_c and decreases monotonically with decreasing T_c to zero for $T_c \lesssim 75$ K. The Hall conductivity σ_{xy} vs magnetic field B data have been analyzed using the expression $\sigma_{xy} = C_1/B + C_2 B$, where the two terms are associated with motion of the magnetic vortices and the quasiparticles in the vortex cores, respectively, yielding C_1 and C_2 as functions of x, y, and T.

From our analysis of the resistive transitions p(T) of superconducting thin films of $Nd_{1.85}Ce_{0.15}CuO_{4\pm\delta}$ with different oxygen contents, we inferred the existence of a vortex-glass transition for an optimally doped film with a $T_c \approx 22$ K. The irreversibility line determined by the vortex-glass transition temperature $T_G(H)$ exhibits a power-law dependence $H(T_G) \propto (1 - T_G(H)/T_{c_0})^{2.0}$. From a scaling analysis of the fluctuation conductivity, we deduced the zero-field transition temperature $T_{c_0} = (21.9 \pm 0.1)$ K, the zero-temperature upper critical field $H_{c_2}(0) = (80 \pm 5)$ kOe, and an in-plane zero-temperature coherence length $\xi_{ab}(0) = (64 \pm 2)$ Å. For an overoxygenated film with $T_c \approx 10$ K, we observe a characteristic,low-temperature ($T \lesssim 2$ K) anomaly in p(T) for $H \parallel c$ that closely resembles the behavior found in NCCO single crystals and could be due to the magnetic ordering of the Nd ions.

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