Change in the sign of the fluctuational Hall conductivity of $YBa_2Cu_3O_{7-\delta}$ epitaxial films

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The Hall and longitudinal resistances ρ_{xy} and ρ_{xx} of $YBa_2Cu_3O_{7-\delta}$ epitaxial films have been measured at $80 < T < 185$ K. The fluctuational component of the Hall conductivity $\sigma_{xy}=\rho_{xy}/(\rho_{xy}^2+\rho_{xx}^2)$ changes sign at $T > T_c$. Recent theoretical studies indicate that this change may signify a change in the sign of an imaginary part of the relaxation time of the order parameter.

The change in the sign of the Hall resistance of high-T_c superconductors near T_c remains the subject of active debate.[1] Recent progress toward a theoretical explanation of this effect has been made by an approach which is based on the Ginzburg–Landau theory. In this approach, the relaxation time of the order parameter γ is treated as a complex quantity.[2,3] The fluctuational component of the Hall conductivity turns out to be proportional to $\lambda_0^{-1}=\mathrm{Im}(\gamma)$.[2]

In the present letter we analyze the Hall conductivity $\sigma_{xy}=\rho_{xy}/(\rho_{xy}^2+\rho_{xx}^2)$ of the high-T_c superconductor $YBa_2Cu_3O_{7-\delta}$. The conductivity was found from measurements of the Hall and longitudinal resistances ρ_{xy} and ρ_{xx}, respectively. The fluctuational Hall conductivity was found by subtracting the normal component σ_{xy}^n from the experimental values of σ_{xy}: $\sigma_{xy}^{fl}\sigma_{xy}-\sigma_{xy}^{n}$. It was found that σ_{xy}^{fl} changes sign, from a positive value corresponding to the sign of σ_{xy}^{n}, to a negative value, which corresponds to the sign of σ_{xy} in the mixed state.

The $YBa_2Cu_3O_{7-\delta}$ epitaxial films were grown at the Institute of Applied Physics, Russian Academy of Sciences, in Nizhniĭ Novgorod, on a $SrTiO_3$ substrate by a laser deposition method. The film thickness was 1000 Å. The transition temperature in a zero field was $T_c \approx 90$ K, and the transition width was < 1 K. The Hall resistance was measured by a method involving a switching of pairs of contacts. We had used this method previously to study $Bi_2Sr_2CaCu_2O_x$ single crystals.[4] The linearity of the voltage in the (direct) current was checked in the range 100–1000 μA in all magnetic fields ($0.2 < H < 4$ T) and at all temperatures ($80 < T < 185$ K). Many of the results were found at a measurement current of 600 μA, which corresponds to a current density $j \approx 1200$ A/cm^2. A silver layer was deposited on the film where the film was connected to the clamp contacts. This silver kept the contact resistance at $< 1\ \Omega$. The Hall voltage was measured with a Keithley 181 nanovoltmeter. The error in the measurements of the Hall resistance was 0.1%. Since there were eight contacts on each sample, it was possible to carry out three independent measurements of the Hall resistance. The variations in the results found for ρ_{xy} for one film were $\leqslant 3\%$. This variation (within a factor of 1.03) remains the same, within the experimental errors,

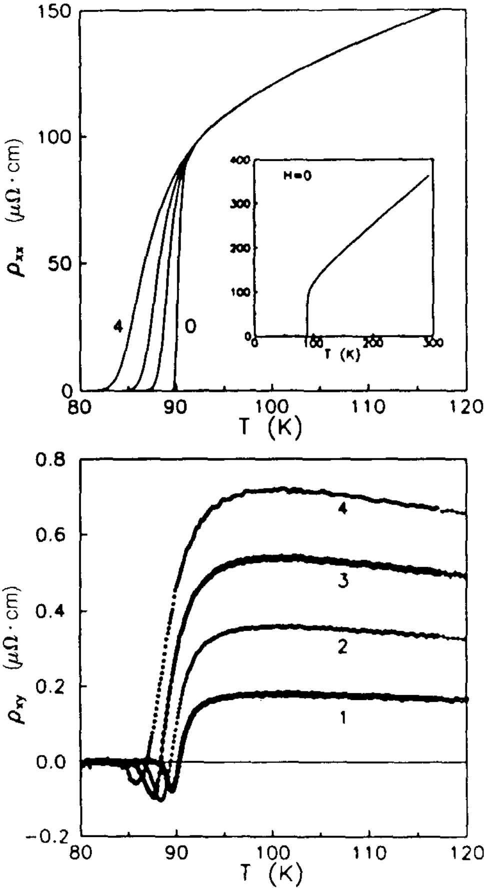

FIG. 1. Upper panel: Temperature dependence of ρ_{xx} in magnetic fields of 0, 1, 2, and 4 T. The inset shows $\rho_{xx}(T)$ at $H=0$ up to room temperature. Lower panel: Temperature dependence of ρ_{xy} in various magnetic fields (the curve labels, in teslas).

in the entire temperature range, indicating that the sample was very nearly homogeneous. The absolute error in the temperature measurements was 0.1%.

Figure 1 shows the temperature dependence of ρ_{xx} and ρ_{xy} in magnetic fields up to 4 T. The inset shows $\rho_{xx}(T)$ at $H=0$. The deviation of the resistance from a linear law and the negative curvature of $\rho_{xx}(T)$ are associated with fluctuations (Ref. 5, for example). In magnetic fields, the resistive transition "broadens." Ullah and Dorsey[2] have described the temperature dependence of the transport coefficients near T_c from a common standpoint, involving the motion of the order parameter with an interaction of fluctuations. The $\rho_{xx}(T)$ dependence in a magnetic field has a crossover from a fluctuation region in the mixed state, in which the dissipation is determined by a motion of vortices. This is the reason for the broadening of the transition. Along that approach, the crossover point is taken to be $T_c(H)$.

We see in Fig. 1 that the Hall resistance changes sign. The study which we are reporting in this paper was the result of an effort to find an explanation for this effect.

The lower panel in Fig. 2 shows the temperature dependence of σ_{xy}. In the normal

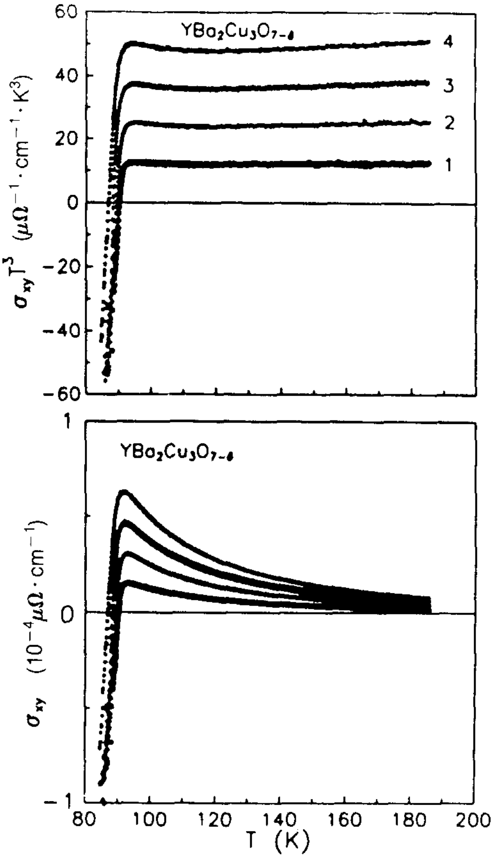

FIG. 2. Upper panel: Temperature dependence of $\sigma_{xy}T^3$ in various magnetic fields (the curve labels, in teslas). Lower panel: Temperature dependence of $\sigma_{xy}(T)$ in magnetic fields of (from bottom to top) 1, 2, 3, and 4 T.

state the Hall conductivity is proportional to the magnetic field and is very sensitive to the temperature. It has been shown[6] in experiments on $YBa_2Cu_3O_{7-\delta}$ single crystals that the relation $\sigma_{xy} \propto 1/T^3$ holds in the normal state (to 360 K). Anderson[7] has explained this behavior in terms of a spinon–spinon scattering, which contributes to ρ_{xy}, and a holon–spinon scattering, which contributes to ρ_{xx}. Without getting involved in the validity of that interpretation, we can treat a relationship $\sigma_{xy} \propto 1/T^3$ as empirical, valid over a broad temperature range. To illustrate the situation, we show in the upper panel in Fig. 2 some curves of $\sigma_{xy}T^{3(T)}$ in the same magnetic fields as for the lower panel. In the normal region we have $\sigma_{xy}T^3(T) \approx$const, although we do see a slight increase in $\sigma_{xy}T^3$ with increasing temperature, in agreement with Ref. 6. The deviation of the Hall conductivity from the $\sigma_{xy}=aH/T^3$ law [where $a=12$ $(\mu\Omega\cdot\mathrm{cm}\cdot T)^{-1}\cdot \mathrm{K}^3$] at $110<T<185$ K and $1<H<4$ T amounts to $\delta\sigma_{xy}/H<1.5\times10^{-7}$ $(\mu\Omega\cdot\mathrm{cm}\cdot T)^{-1}$.

This inset in Fig. 3 shows the temperature dependence of $\sigma_{xy}T^3$ near T_c. In order to show data for the different fields, we have normalized σ_{xy} to the magnetic field. As the temperature is lowered below 110–105 K, there is a sharp deviation from the $\sigma_{xy} \propto 1/T^3$ law; as the temperature is lowered 10 K (from 105 to 95 K), this deviation

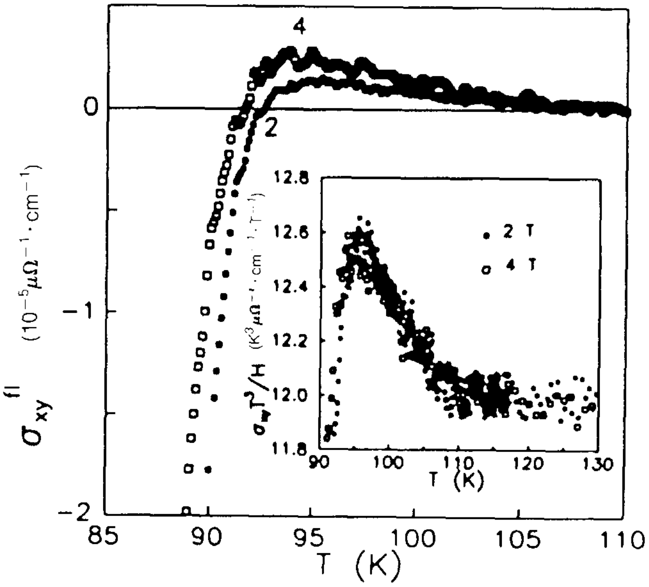

FIG. 3. Temperature dependence $\sigma_{xy}^{fl}(T)$ in magnetic fields of 2 and 4 T. The inset shows the temperature dependence of $\sigma_{xy}T^3/H$ near T_c.

amounts to $\Delta\sigma_{xy}/H \approx 5.5\times10^{-7}$ $(\mu\Omega\cdot\text{cm}\cdot T)^{-1}$. In the same temperature range, various physical properties of $YBa_2Cu_3O_{7-\delta}$ [the longitudinal electrical resistance, the magnetization (Ref. 5, for example), the Ettinghausen coefficient,[8] and the heat capacity[9]] deviate substantially from their normal-state behavior. These deviations are characteristic of a transition into a fluctuation region.[5,2] It is natural to attribute to fluctuation the deviations from the $\sigma_{xy} \approx aH/T^3$ dependence, which holds to 185 K (to 360 K according to the results of Ref. 6). Figure 3 shows the temperature dependence of the fluctuation increment, found as $\sigma_{xy}^{fl} = \sigma_{xy} - \sigma_{xy}^{n}$, with $\sigma_{xy}^{n} = 12\ H/T^3$ $[(\mu\Omega\cdot\text{cm})^{-1}]$, for magnetic fields of 2 and 4 T. The quantity σ_{xy}^{fl} changes sign at $T^* \approx 92$ K—at a temperature above the transition in a zero magnetic field. Chien *et al.*[6] have also observed a deviation from $\sigma_{xy} \propto 1/T^3$ at 105–110 K. They attributed it to fluctuations, but they did not report data for lower temperatures.

The sign of σ_{xy}^{fl} at $T > T^*$ is the same as the sign of the Hall conductivity in the normal state. Aronov, Rapoport, and Larkin[10] have shown that for the case of noninteracting fluctuations and $\partial T_c/\partial n > 0$, where n is the carrier density, the signs of σ_{xy}^{fl} and σ_{xy}^{n} must be the same. Since we have[11] $\partial T_c/\partial n > 0$ for $YBa_2Cu_3O_{7-\delta}$, the change in the sign of σ_{xy}^{fl} apparently means a transition into a region of critical fluctuations. In the high-T_c superconductors, this region is much wider than in "ordinary" type-II superconductors, because of the large value of the Ginzburg–Landau parameter κ, the short coherence length, and the high value of T_c (Ref. 5). Fukuyama *et al.*[12] have shown that we would have $\sigma_{xy}^{fl} \propto H$ for an Aslamazov–Larkin fluctuation process. A deviation from this behavior (Fig. 3) is further evidence of a transition into a critical region.

In the theory of Ref. 2, which incorporates a correlation of fluctuations, the sign of σ_{xy}^{fl} is determined by the sign of $\lambda_0^{-1} = \mathrm{Im}(\gamma)$. The quantity λ_0^{-1} was calculated in Ref. 12 for noninteracting fluctuations; this quantity turned out to be proportional to $(\partial\nu/\partial E)|_{E=\epsilon_F}$, where ν is the density of states, and ϵ_F is the Fermi energy. The change in the electron spectrum as the temperature approaches T_c apparently has a dramatic effect on the parameter λ_0^{-1}.

As the temperature is lowered further, σ_{xy}^{fl} increases in absolute value. At a certain temperature ($\approx$90.2 K for 1 T and $\approx$87.2 K for 4 T), it changes sign, going negative, like σ_{xy}. In the mixed state, the fact that the Hall conductivity has the sign opposite that of σ_{xy}^n means that the projection of the vortex velocity vector onto the transport current is negative.

It follows from this study that the effect which is ultimately responsible for the change in the sign of the Hall conductivity is "nucleated" in a region of critical fluctuations, in which the motion of the vortices cannot yet be assigned a definite sign. A phenomenological approach is inadequate for a detailed study of this effect; a microscopic theory is apparently necessary.

Aronov and Hikami[13] have studied the contribution of skew scattering due to the spin–orbit interaction to the σ_{xy}^{fl} effect, described by a four-point vertex in a Feynman-diagram technique. In other words, they dealt with a higher order than in the ordinary Aslamazov–Larkin process. It was found that the sign of σ_{xy}^{fl} should be opposite that of σ_{xy}^n in this case. It may be that finding an explanation of the results of the present study will require not only treating γ as a complex quantity but also considering the process examined in Ref. 13.

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