Anomalous Hall effect in a ferromagnetic rare-earth cobaltite

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Abstract

Rare-earth manganites and cobaltites with the perovskite structure have been a subject of great, recent interest because their electrical resistance changes significantly when a magnetic field is applied [1]-[7], a property, which is of technological relevance for magnetic devices. Depending on the stoichiometry, these compounds have different magnetic ordering states, and the understanding of the interaction of the conduction electrons with the magnetic moments of manganese or cobalt ions is important for explaining the origin of the "colossal magnetoresistance" effect [1]-[7]. In order to obtain direct information about the scattering of the conduction electrons by localized magnetic moments, we have studied the Hall effect in thin film $La_{0.5}Ca_{0.5}CoO_3$ material and have obtained convincing evidence for the so-called "anomalous" Hall effect, typical for magnetic metals. This effect is due to the left-right asymmetry of conduction electron scattering by various perturbations in the regular arrangement of the localized moments of the magnetic ions [8]. Our results suggest that near the ferromagnetic ordering temperature, the dominant electron scattering mechanism is the spin fluctuations.

The $La_{0.5}Ca_{0.5}CoO_3$ epitaxial films have been grown by pulsed laser deposition using a stoichiometric target of $La_{0.5}Ca_{0.5}CoO_3$, in 100 mTorr of oxygen. The temperature of the $LaAlO_3$ substrates has been 700 °C. The growth has been followed by annealing at 900 °C for two hours, and the epitaxy of the films is confirmed by x-ray rocking curves. The resistivity and magnetization measurements (N. - C. Yeh *et al.*, manuscript submitted) give the ferromagnetic ordering (Curie) temperature $T_c = 180 \pm 5$ K. The samples are 2 mm×2 mm×200 nm in size. The magnetic field is always perpendicular to the film. The demagnetization factor is $N \approx 1$ in such a geometry, so that the applied magnetic field H_a multiplied by the permeability of vacuum μ_0 equals the magnetic induction B in the film.

Figure 1 shows the temperature dependence of the electrical resistivity ρ_{xx} in zero magnetic field. A large decrease in the resistivity is observed near T_c, which is followed by a minimum and a subsequent increase of ρ_{xx} with decreasing temperature. Such a rapid increase of the resistivity at low temperatures is common in cobaltites with the perovskite structure [10]. The magnetic field dependence of the resistivity is presented in Fig. 2, top panel. The relative change of ρ_{xx} is largest near T_c.

In Fig. 2, bottom panel, we show the Hall resistivity, which is defined as the Hall (transverse) electric field (E_y) per unit longitudinal current density (J_x): $\rho_{xy} = E_y/J_x = R_H B$ (where R_H is the Hall coefficient). The data of Fig. 2, bottom panel, show that in the ferromagnetic state ($T < T_c$) the initial linear rise of ρ_{xy} is followed by a much weaker field dependence with increasing field. As the temperature is increased above the Curie temperature, the deviation from the linear behavior becomes less pronounced and disappears for high enough temperatures in the entire magnetic field range (see the isotherms at $T = 198$ K and at $T = 245$ K in Fig. 2, bottom panel).

The linear portions of the magnetic field dependences of the hall resistivity allow determination of the low-field (field-independent) Hall coefficient, which appears to have a strong temperature dependence (Fig. 3). R_H increases with temperature up to a maximum occuring approximately 15 K below the Curie temperature. The maximum is followed by a rapid drop of the Hall coefficient, with the largest negative temperature slope nearest T_c. The Hall coefficient monotonically decreases with temperature in the paramagnetic state.

Now we proceed to interpret the Hall resistivity data. In magnetic materials, the Hall resistivity can be presented as a sum of two terms [8]: $\rho_{xy} = R_0 B + R_s M$, where M is the magnetization, R_0 and R_s are coefficients of proportionality. The first term can be viewed simply as the result of the Lorentz force on the free electrons, with $R_0 = 1/(ne)$, where n is the electron density, e is the electron charge. The second term is the anomalous Hall resistivity in magnetic materials, and typically $R_s \gg R_0$ in the ferromagnetic state [8]. Having observed the strong magnetic field and temperature dependences of ρ_{xy}, we shall argue in the following discussion that our Hall effect data can be primarily attributed to the anomalous Hall effect.

Let us first consider a single magnetic domain in a ferromagnet. It has in zero applied magnetic field a spontaneous magnetization ($M \neq 0$) and therefore a spontaneous Hall effect inside the domain. This phenomenon is referred to as the anomalous Hall effect [8]. The coefficient of proportionality R_s is determined by the scattering of conduction electrons by disorder in the system of the localized magnetic moments [8,11,12]. For a large number of randomly oriented domains the average magnetization is zero, as is the anomalous Hall resistivity. As the external magnetic field is increased, the domains become progressively more aligned, and the Hall voltage appears. This behavior corresponds to the initial linear rise of the Hall resistivity in small magnetic fields and the gradual saturation in large magnetic fields (Fig. 2, bottom).

The rise of the Hall coefficient with temperature in the ferromagnetic state ($T < T_c$) can be understood in terms of the thermally induced fluctuations of the spins of the cobalt ions. Detailed theory [11,12] predicts a maximum in the temperature dependence of R_H just below the ferromagnetic ordering temperature, in agreement with the data of Fig. 3.

Next, we consider the paramagnetic state. Just as an applied magnetic field aligns macroscopic magnetic domains at $T < T_c$ to produce the anomalous Hall effect, so can it align the individual ionic moments at $T > T_c$ to produce a similar effect [12]. The degree of this alignment at $T > T_c$ is proportional to $M = \chi H_a$, where χ is the magnetic susceptibility. Therefore, the Hall resistivity in the paramagnetic state is expected to be proportional to the magnetic field, in agreement with the data (Fig. 2, bottom panel). The anomalous Hall coefficient R_s has been shown theoretically to be nearly temperature-independent in the paramagnetic state [12]. Consequently, the temperature dependence of $\rho_{xy} = R_s \chi H_a$ should follow that of the magnetic susceptibility: $\chi \sim (T - T_c)^{-1}$. This point can be verified by plotting the inverse Hall coefficient as a function of temperature (Fig. 4). Indeed, $1/R_H$ is linear with temperature above $T_c \approx 180$ K.

Finally, we consider the implications of the observed anomalous Hall effect on the magnetoresistance. In Fig. 3, the magnitude of the relative change of ρ_{xx} in a field of 6.5 T, defined as $[\rho_{xx}(6.5T) - \rho_{xx}(0)]/\rho_{xx}(0)$, is shown by the squares and a dashed line. The peak feature near T_c correlates well with the anomalous Hall effect data, indicating that the spin fluctuations play an important role in the occurrence of the large negative magnetoresistance. Such an effect should be of general importance to the magnetoresistance in the magnetic perovskites of cobaltites as well as manganites, although additional complications may arise due to the existence of the Jahn-Teller effect in the latter [13]. Quantitative studies of the correlation between R_s and ρ_{xx} will be necessary for further understanding of this issue [14].

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FIGURE CAPTIONS

Fig 1. The temperature dependence of the electrical resistivity in zero applied magnetic field. 'I 'he arrow indicates the Curie temperature T_c.

Fig. 2. Top, the magnetic field dependences of the relative change of the longitutinal resistivity. The temperature is indicated near the curves. Bottom, the rllaglictic.field dependences of the Hall resistivity. The solid lines are guides to the eye, The dashed lines in the bottom panel present the linear slope of ρ_{xy} at low fields. For the Hall measurements, we have deposited four gold pads on the corners of the film and employed the van der Pauw method [9] to measure both the Hall and longitudinal resistivities. We have p erformed measurements at 10 - 20 different values of clec.tried current in the range O - 30 μA for all temperatures and magnetic fields to ensure linear response of the system. The sign of ρ_{xy} is positive. Although the magnetization curves measured on the bulk $La_{0.5}Ca_{0.5}CoO_3$ material look similar to the field dependences of ρ_{xy}, quantitative comparison is difficult because of the difference in the demagnetization factors of the thin film and bulk samples.

Fig. 3. The temperature dependences of the Hall coefficient (circles) and the magnetoresistance in a field of 6.5 T (squares). The solid and dashed lines arc guides to the eye .

Fig. 4. The temperature dependence of the inverse hall coefficient. The solid line is a linear fit to the high temperature data points, which satisfies $R_H^{-1} \sim$ (7' - T_c), and $T_c \approx 180$ K. Assuming that the normal Hall coefficient $R_0 =$ 1 /(ne) does not exceed the value of R_H at 290 K, one obtains a lower limit for the carrier density $n > 6 \times 10^{26} m^{-3}$.

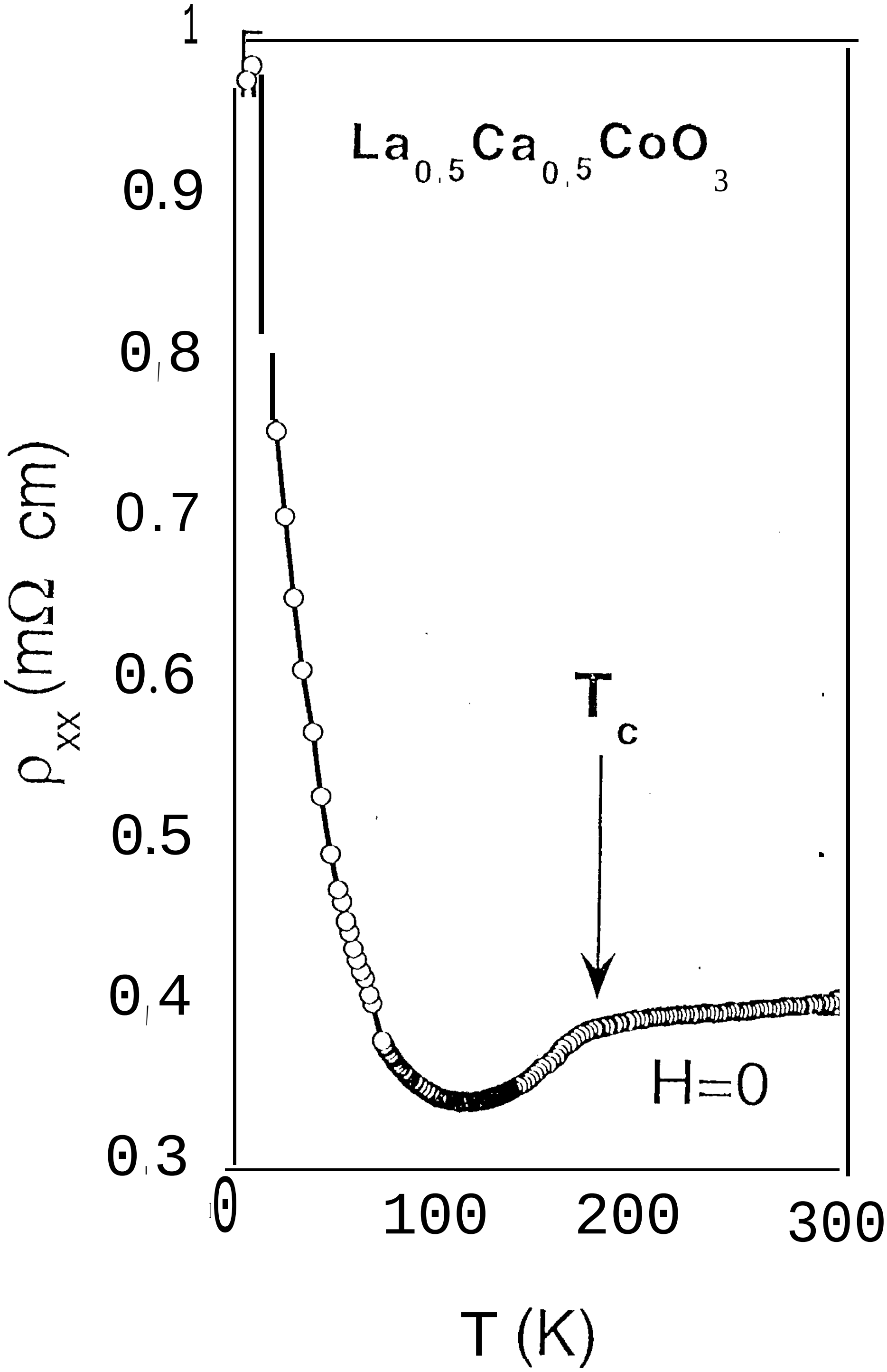

Fig. 1.
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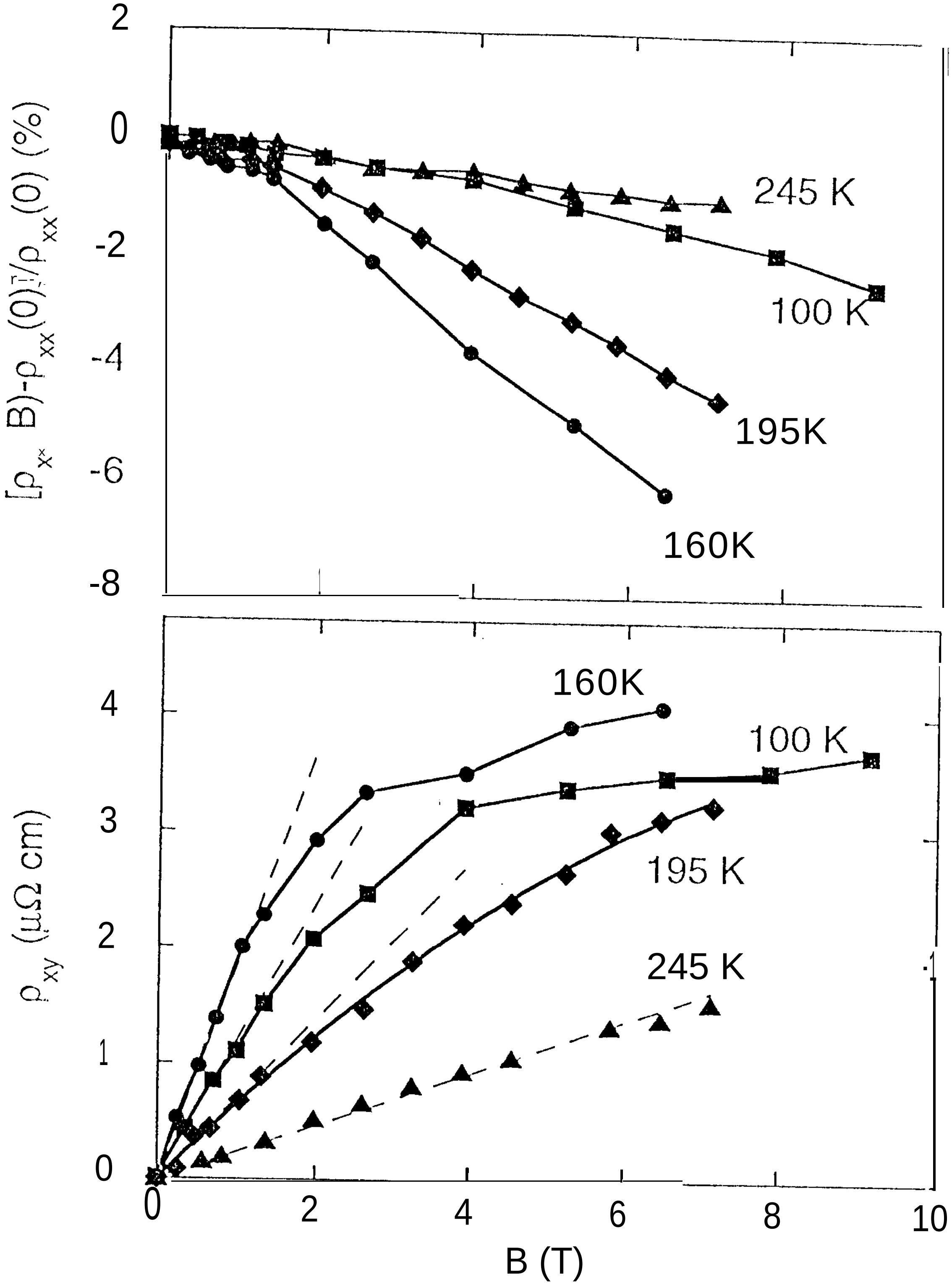

Fig. 2
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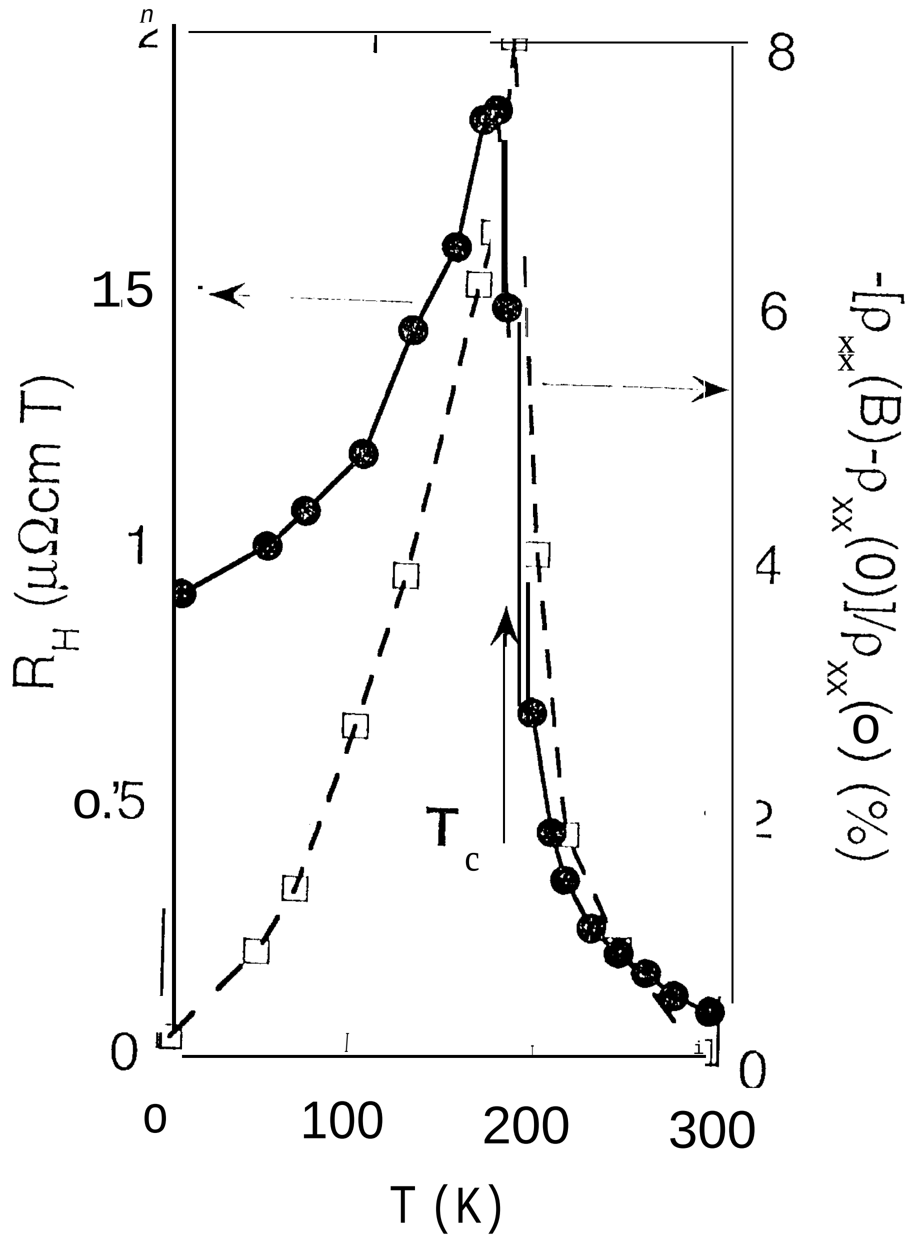

Fig. 3
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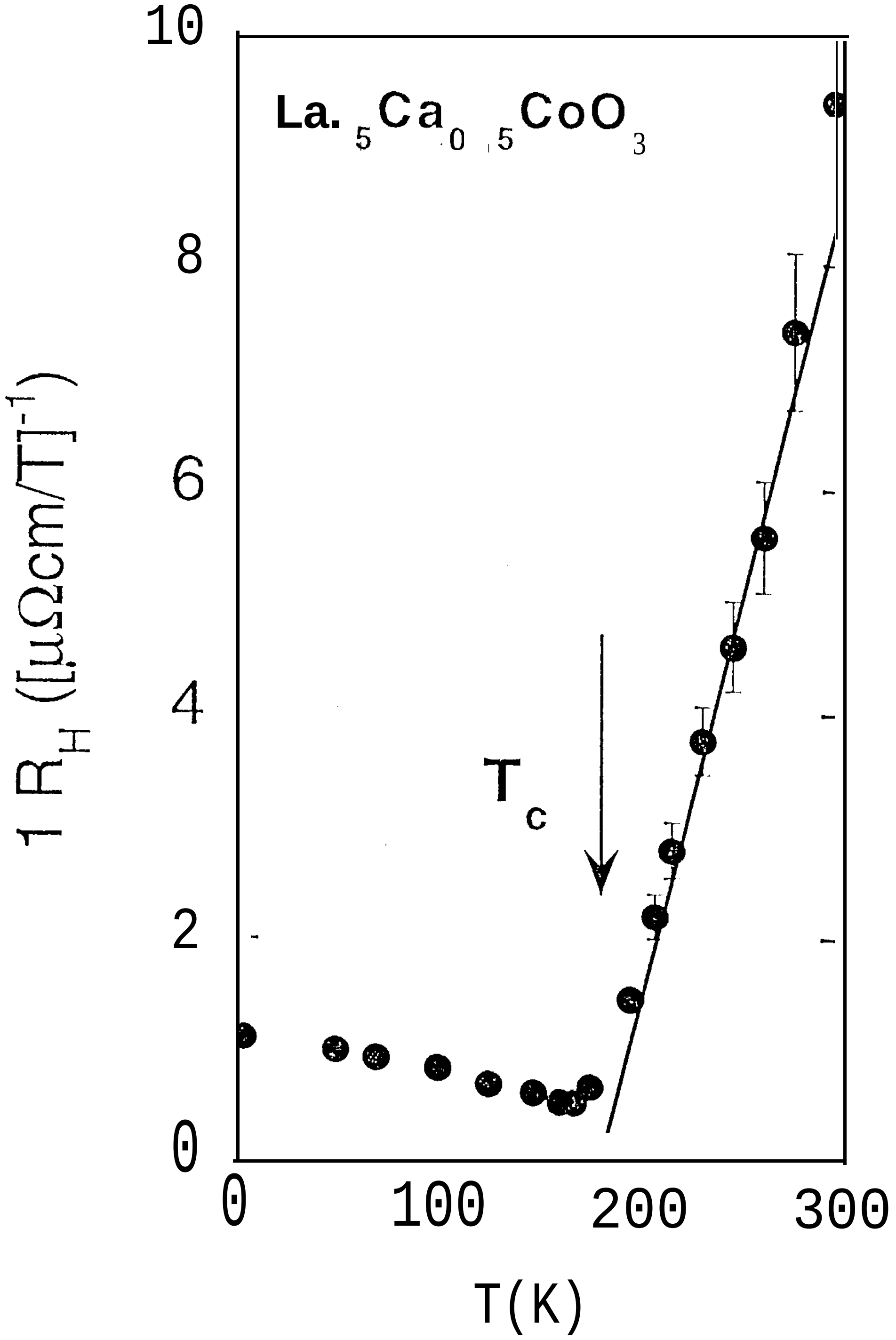

Fig. 4
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