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TITLE: ANOMALOUS MAGNETORESISTANCE BEHAVIOR OF SUPERCONDUCTING $Nd_{2-x}Ce_xCuO_{4-y}$ SINGLE CRYSTAL

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Anomalous magnetoresistance behavior of superconducting $Nd_{2-x}Ce_xCuO_{4-y}$ single crystal

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Abstract

Magnetoresistance measurements on a superconducting $Nd_{2-x}Ce_xCuO_{4-y}$ single crystal with $T_c \approx 7$ K were made with magnetic fields H applied parallel (H ‖ c) and perpendicular (H ⊥ c) to the tetragonal c-axis. For H ‖ c, the resistive superconductive transition curves exhibit a double transition at low temperatures and high magnetic fields. This double resistive transition has a maximum near $T \approx 1.1$ K, followed by an extremely sharp transition into the superconducting state. For applied fields of 1kOe, the resistivity first goes to zero, increases again to a finite value and then goes through a second transition. In this region, the resistivity exhibits non-ohmic behavior for low current densities and ohmic behavior for larger measuring currents. The resistivity for H ⊥ c does not exhibit any anomalous behavior or a maximum for $0 \leq H \leq 60$ kOe and $4 \leq T \leq 7$ K.

Running Title: Anomalous magnetoresistance of superconducting $Nd_{2-x}Ce_xCuO_{4-y}$ single crystal

Keywords: Single crystal, magnetoresistance, phase transition, $Nd_{2-x}Ce_xCuO_{4-y}$

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Investigations on the new high temperature superconductors (HTSC) discovered after 1986 have revealed a much richer magnetic field H-temperature T phase diagram than in conventional superconductors.[1] The H-T phase diagram has been widely studied in hole-doped superconductors in contrast to their electron-doped counterparts for which no systematic study has been made. The $Ln_{2-x}M_xCuO_{4-\delta}$ (Ln = Nd, Sm, Pr, Eu; M = Ce, Th) system is particularly interesting because it is one of the simplest system of cuprate superconductors and one of the few cuprate systems in which superconductivity is induced by doping with electrons, instead of holes, although it must also be partially reduced ($\delta \approx 0.02$).

In this paper, we report results of an investigation of the H-T phase diagram in the low temperature region by means of magnetoresistivity $\rho(T,H)$ measurements on a superconducting single crystal of $Nd_{2-x}Ce_xCuO_{4-y}$ with $T_c \approx 7$ K. Our results show that two distinct superconducting transitions appear in applied magnetic fields with a second sharp drop in resistivity to zero at low temperatures and in high magnetic fields.

The single crystal of $Nd_{2-x}Ce_xCuO_{4-y}$ used in this experiment was grown using the self-flux method. The crystal was checked by x-ray diffraction and found to show a high degree of alignment with the c-axis perpendicular to the largest face. Within the sensitivity of the equipment, no additional phases were detected. Magnetoresistance measurements were performed in a ^3He-^4He dilution refrigerator in magnetic fields up to 60 kOe applied both parallel and perpendicular to the c-axis using a low frequency (16 Hz) ac four wire bridge. Magnetic susceptibility measurements were performed using a Quantum Design SQUID magnetometer with an applied dc magnetic field of 1 Oe.

Shown in Fig. 1 are the resistive transition curves for the $Nd_{2-x}Ce_xCuO_{4-y}$ single crystal ($T_c = 7$ K) in magnetic fields H for $H \parallel c$ and $H \perp c$ and the current in the basal plane. The inset of Fig. 1(b) shows the electrical resistivity ρ in the basal plane in zero applied magnetic field. The application of a magnetic field H in both directions results in the expected nearly parallel shift of the transition for fields below 1 kOe, a characteristic behavior for the electron-doped $Ln_{2-x}M_xCuO_{4-y}$ single crystal. The effect of magnetic field is more dramatic for fields between 1 kOe and 2 kOe as shown in Fig. 1(a). In this range, an unusual dependence on applied field becomes apparent around 1 kOe; ρ(T) initially decreases with temperature, then increases below 2 K, and finally goes through a maximum around 1.1 K, before it undergoes a second transition that is much sharper than the initial one. The sharpness of this second transition increases with increasing magnetic field. Similar anomalous behavior was also observed in two other single crystals with approximately the same critical temperature as the one reported on here. It is interesting to note that 1.1 K, the temperature where the second transition develops, is also close to the temperature for antiferromagnetic ordering of the Nd^{3+} ions. For $H \perp c$, the resistive transitions do not show anomalous behavior and still follow a parallel-shift behavior up to applied fields of 60 kOe. The data in Fig. 1 also display a resistivity peak near the superconducting transition. The magnitude of the peak initially increases and then decreases with increasing magnetic field.

In order to elucidate the anomalous behavior under applied field a systematic study of the current dependence of the resistivity for currents up to 400 μA under an applied magnetic field H = 1.4 kOe was performed. Figure 2 illustrates the effect of increasing measuring current on ρ(T) for $300\ \mu A \leq I \leq 400\ \mu A$ and $T < 5$ K. We note that the effect of increasing current density is insignificant above 3.4 K. The overall trend of the data below 3.4 K is towards a monotonic increase of the resistivity with increasing current up to 400 μA. For currents higher than 400 μA, the effect on the resistivity saturates in that further increase of I does not have any effect on ρ. Two noteworthy features emerge from this plot: (1) The resistivity maximum of the second transition ($T \approx 1.1$ K) has a small but systematic shift with increasing current and, (2) the resistivity maximum of the first transition occurs approximately at the same temperature ($T \approx 3.6$ K) regardless of the magnitude of the measuring current. Measurements with currents higher that 400 μA were not possible due to Joule heating from the current contacts to the sample. Measurements of I-V curves at fixed temperatures of 0.5 K, 1.1 K, and 2.7 K for applied field H = 1.4 kOe, shown in Fig. 2(b), confirm the existence of two distinct regimes, one corresponding to non-ohmic behavior for currents below 300 μA, and the other exhibiting ohmic behavior for currents above 300 μA. Near the transition onset ($T \approx 2.7$ K), the behavior is much closer to ohmic than at T = 1.1 K and 0.5 K where the increase is strongly nonlinear in the low current region.

One possibility to account for the observed anomalous behavior could be associated with a phase transition to a vortex glass state similar to what was proposed by Worthington et al.[2] in experiments with $YBa_2Cu_3O_{7-\delta}$ single crystals. This would be intimately connected with the intermediate strength of disorder in this single crystal. In this case the disorder is characterized by a low Meissner fraction (~ 1%) and low residual resistivity ratio $\rho(300\ K)/\rho(20\ K) \sim 2.5$.

Another possible scenario that could account for the anomalous behavior of the magnetoresitivity is in terms of the granular model proposed by Shih, Ebner, and Stroud.[3] In this picture, which has also been used by Early et al.[4] to explain the double resistive superconducting transition in $Sm_{2-x}Ce_xCuO_{4-y}$ polycrystals, the single crystals are viewed as an array of superconducting islands weakly connected through a metallic matrix as a result of inhomogeneous cationic (i.e., Ce) and/or anionic (i.e., O) distributions.

The present study reveals the existence of a anomalous temperature dependence of magnetoresistivity and, in particular, the existence of two distinct resistive transitions present in a $Nd_{2-x}Ce_xCuO_{4-y}$ single crystal. We have discussed this anomalous behavior within the context of vortex-glass and granular superconductor pictures. Overall, the reduction of T_c has a dramatic effect on the superconducting properties of the Nd-Ce-Cu-O system.

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FIGURE CAPTIONS:

Fig. 1 Electrical resistivity ρ as a function of temperature T for a $Nd_{2-x}Ce_xCuO_{4-y}$ single crystal with $T_c = 7$ K in applied magnetic fields H up to 6 T; (a) $H \parallel c$ and (b) $H \perp c$. Inset: $\rho(T)$ in the (a,b) plane for H = 0.

Fig. 2 (a) Electrical resistivity ρ versus temperature T in an applied field H = 1.4 kOe for a $Nd_{2-x}Ce_xCuO_{4-y}$ single crystal with $T_c = 7$ K. The measuring current I was varied between 30 μA and 400 μA. (b) Isothermal electrical resistivity ρ versus current density J for the $Nd_{2-x}Ce_xCuO_{4-y}$ single crystal for H = 1.4 kOe

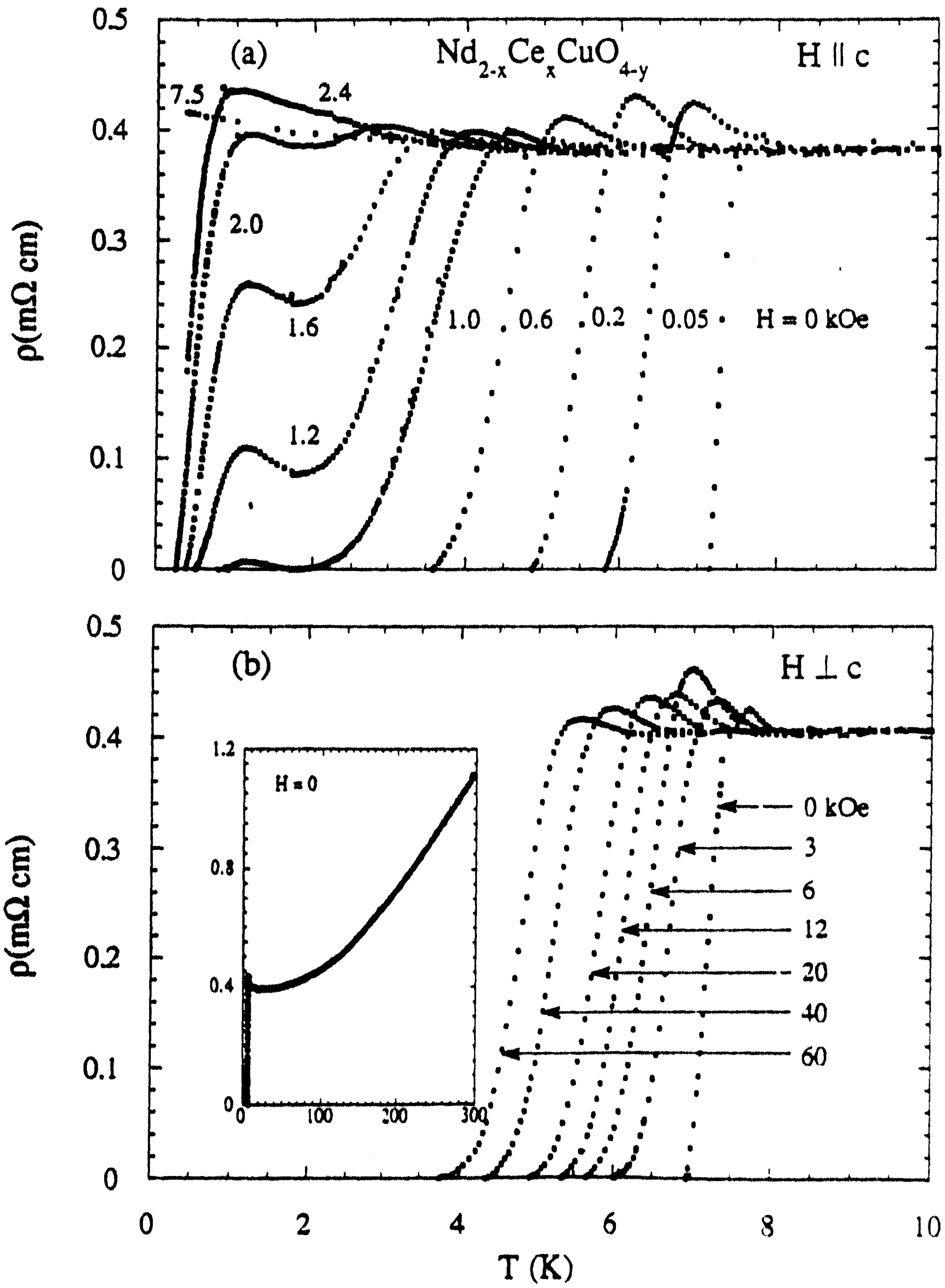

Fig.1
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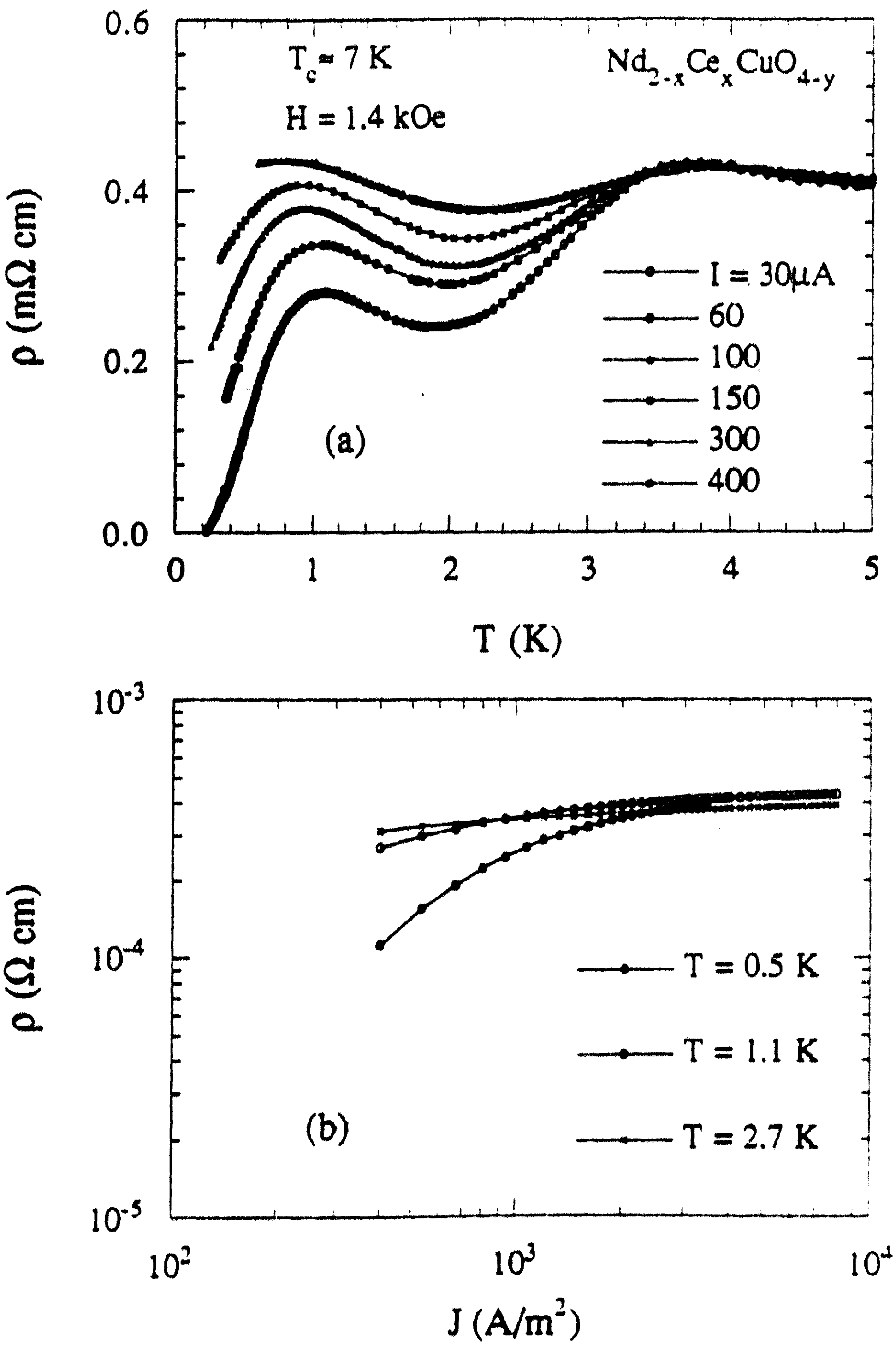

Fig.2
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