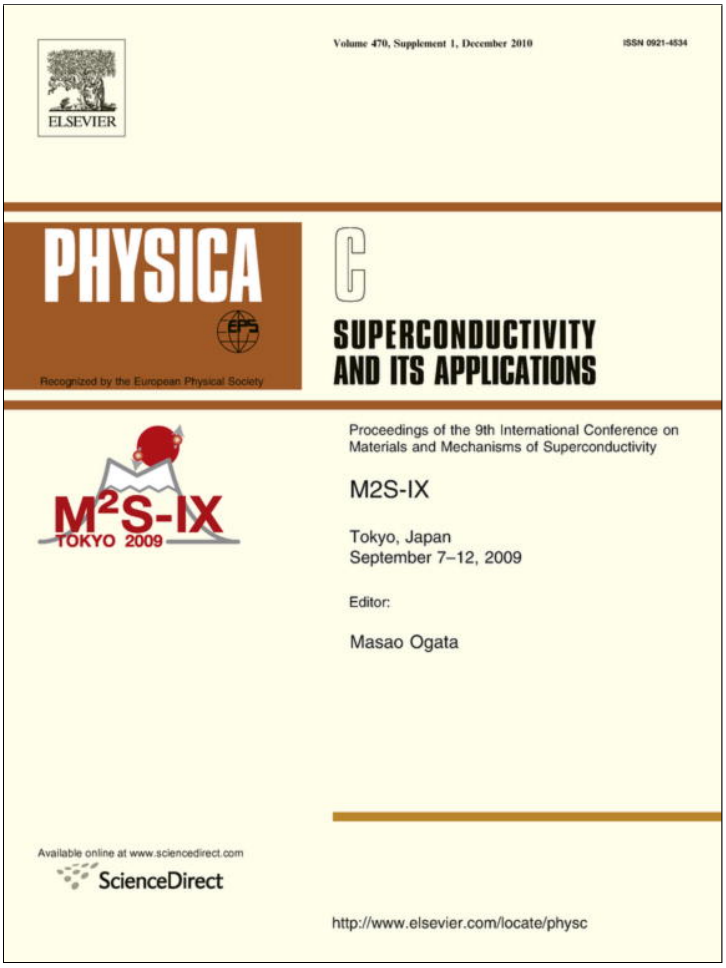
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Zooming on the quantum critical point in Nd-LSCO

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ABSTRACT

Recent studies of the high-T_c superconductor $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (Nd-LSCO) have found a linear-T in-plane resistivity ρ_{ab} and a logarithmic temperature dependence of the thermopower S/T at a hole doping $p = 0.24$ and a Fermi-surface reconstruction just below $p = 0.24$ [1,2]. These are typical signatures of a quantum critical point (QCP). Here we report data on the c-axis resistivity $\rho_c(T)$ of Nd-LSCO measured as a function of temperature near this QCP, in a magnetic field large enough to entirely suppress superconductivity. Like ρ_{ab}, ρ_c shows an upturn at low temperature, a signature of Fermi surface reconstruction caused by stripe order. Tracking the height of the upturn as it decreases with doping enables us to pin down the precise location of the QCP where stripe order ends, at $p^* = 0.235 \pm 0.005$. We propose that the temperature T_ρ below which the upturn begins marks the onset of the pseudogap phase, found to be roughly twice as high as the stripe-ordering temperature in this material.

One of the central questions of high-T_c superconductivity is the nature of the pseudogap phase. Recent quantum oscillation studies [3] favour a scenario of competing order, as they reveal that the large hole-like Fermi surface of overdoped cuprates [4] transforms into small electron-like pockets in the pseudogap phase [5]. This shows that there is some "hidden" order in the pseudogap phase which breaks translational symmetry and thus causes a reconstruction of the Fermi surface [6]. In some cuprates, such as $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (Nd-LSCO), there is clear evidence for charge/spin order, better known as "stripe order", setting in at low temperature (see Ref. [7] and references therein), and the pseudogap phase may be a precursor to that stripe phase.

The presence of an order in the phase diagram involves the presence of a quantum critical point (QCP) at a critical doping p^* where the ordering temperature T^* goes to zero. In Nd-LSCO at a hole-doping of $p = 0.24$, the in-plane resistivity ρ_{ab} is linear down to the lowest temperature [1], and the thermopower S has a $T\ln(1/T)$ dependence over a decade of temperature [2]. These are typical signatures of a quantum phase transition for a metal with two-dimensional antiferromagnetic fluctuations [8,9].

In this letter, we present measurements of the c-axis resistivity ρ_c in Nd-LSCO as a function of temperature T in the vicinity of the QCP. These out-of-plane measurements reveal the same behavior as found in the in-plane data, namely a linear-T resistivity down to a temperature T_ρ below which $\rho(T)$ starts to deviate upwards [1]. In-plane data at $p = 0.20$ and $p = 0.24$ show that T_ρ goes to zero between these two dopings (see Fig. 1). Here we use c-axis samples at intermediate dopings to pin down with greater accuracy the critical doping p^* where $T_\rho \to 0$.

The four samples of Nd-LSCO used in this study were grown at the University of Texas, as described elsewhere [1]. They have a doping of $p = 0.20$, 0.22, 0.23, and 0.24, respectively. The resistivity ρ_c was measured at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, in steady magnetic fields up to 45 T.

Our ρ_c data in a field of 45 T is presented in Fig. 2. (Note that there is negligible magneto-resistance in all cases.) A linear fit to the data below 80 K is shown as a solid line. In the inset, we plot $\Delta\rho_c$, the difference between data and fit. At $p = 0.24$, we see that $\rho_c(T)$ remains linear down to the lowest temperature, as previously reported [1]. At lower doping, an upturn is observed below a temperature T_ρ (see arrows in inset) which is plotted vs. doping in Fig. 1 (red[2] circles). The values of T_ρ obtained from ρ_c are seen to

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[2] For interpretation of colour in Figs. 1 and 2, the reader is referred to the web version of this article.

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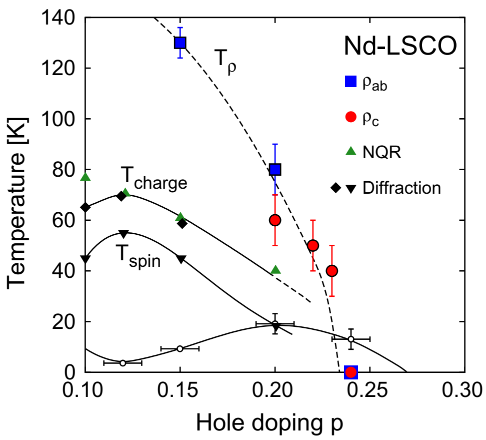

Fig. 1. (Color online) Phase diagram of Nd-LSCO. Temperature T_ρ (blue squares for in-plane, red circles for c-axis) is defined as the temperature below which the normal-state resistivity ρ deviates from its linear-T behavior. Data for $p = 0.15$ is from Ichikawa et al. [10]; data for $p = 0.20$ and $p = 0.24$ are from Daou et al. [1]. At $p = 0.24$, $T_\rho = 0$ K because there is no deviation from linearity. The dashed line is a guide-to-the-eye that goes through the various T_ρ points and ends up at the QCP. The onset temperature of NQR (green upward triangles); charge order deduced from X-ray and neutron diffraction (black diamonds) [7]; and stripe order seen by neutron diffraction (black downward triangles) [10] are also shown. We can then see that $T_\rho \approx 2T_{\text{charge}}$. Superconducting transition temperature T_c (open black circles) is also plotted.

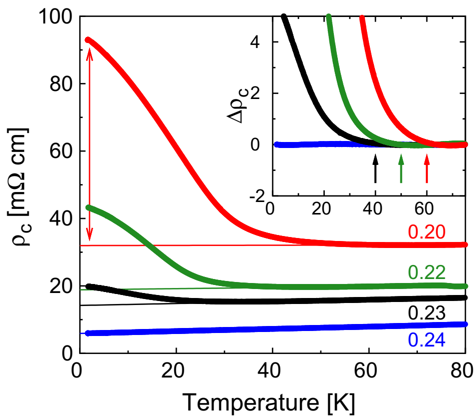

Fig. 2. (Color online) c-Axis resistivity ρ_c of Nd-LSCO at $p = 0.20, 0.22, 0.23$, and 0.24 (top to bottom) as a function of temperature T at 45 T. Linear fit plot as a coloured line under data. The red double-headed arrow shows how we define $\Delta\rho_c(0)$ of Fig. 3. Inset: difference between data and their fits $\Delta\rho_c$ vs. T. This yields $T_\rho = 60 \pm 10, 50 \pm 10$, and 40 ± 10 K for $p = 0.20$, 0.22, and 0.23, respectively. By our definition $T_\rho = 0$ K at $p = 0.24$.

agree well with the overall doping dependence of T_ρ obtained from ρ_{ab} (reproduced from Ref. [1]).

Another way to describe the evolution of the c-axis resistivity data is to plot the magnitude of the upturn as a function of doping, defined as $\Delta\rho_c(0)$, the difference between data and fit in the limit of $T \to 0$ (red double-headed arrow in Fig. 2). Fig. 3 shows $\Delta\rho_c(0)$ as a function of doping. It is clear that the strength of the upturn

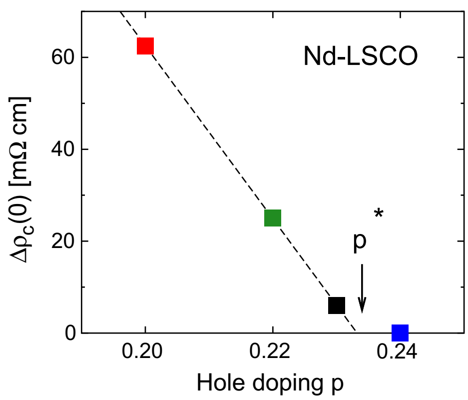

Fig. 3. (Color online) Difference between $\rho_c(T \to 0\text{ K})$ and the linear fit in Fig. 2 evaluated at $T = 0$ K, as a function of doping for Nd-LSCO at $p = 0.20, 0.22, 0.23$, and 0.24. Simple extrapolation to zero shows that the QCP would be located at a doping of $p = 0.235 \pm 0.005$.

goes down as the doping is increased, extrapolating to zero at $p^* = 0.235 \pm 0.005$. This accurately locates the quantum critical point below which Fermi-surface reconstruction begins. We infer that this is where translational symmetry is broken.

As noted previously from in-plane data [1,11], the upturn begins at a temperature significantly above the ordering temperature for stripe order, at T_{charge} (see Fig. 1), with $T_\rho \approx 2T_{\text{charge}}$. This suggests a two-step transformation of the electronic behavior: a first transformation at high temperature, detected in the resistivity and the quasiparticle Nernst signal below T_ν [12], with $T_\rho \simeq T_\nu$, and a second transformation at the stripe ordering temperature, detected in the Hall [1] and Seebeck coefficients [2].

We propose that the temperature $T_\rho \simeq T_\nu$ is in fact the pseudogap temperature T^*. The pseudogap phase would then most likely be a fluctuating precursor of the spin/charge density wave (stripe) order observed at lower temperature (below T_{charge}). This QCP may be a generic feature of hole-doped cuprates. Indeed, recent measurements of c-resistivity in overdoped Bi-2212 crystals show upturns below a temperature T_ρ which also goes to zero at $p \to 0.24$ [13]. Moreover, a reconstruction of the Fermi surface by stripe-like order may also be a more general occurrence, given the very similar anomalies observed in YBCO in both the Hall [5,11] and Seebeck [14] coefficients.

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